Bio-Inspired Approaches for Building Nanoscale Systems

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BNL’s Center for Functional Nanomaterials (CFN)

CFN Scientific Themes

- interface science & catalysis
- electronic materials for photovoltaics
- soft & biomaterials

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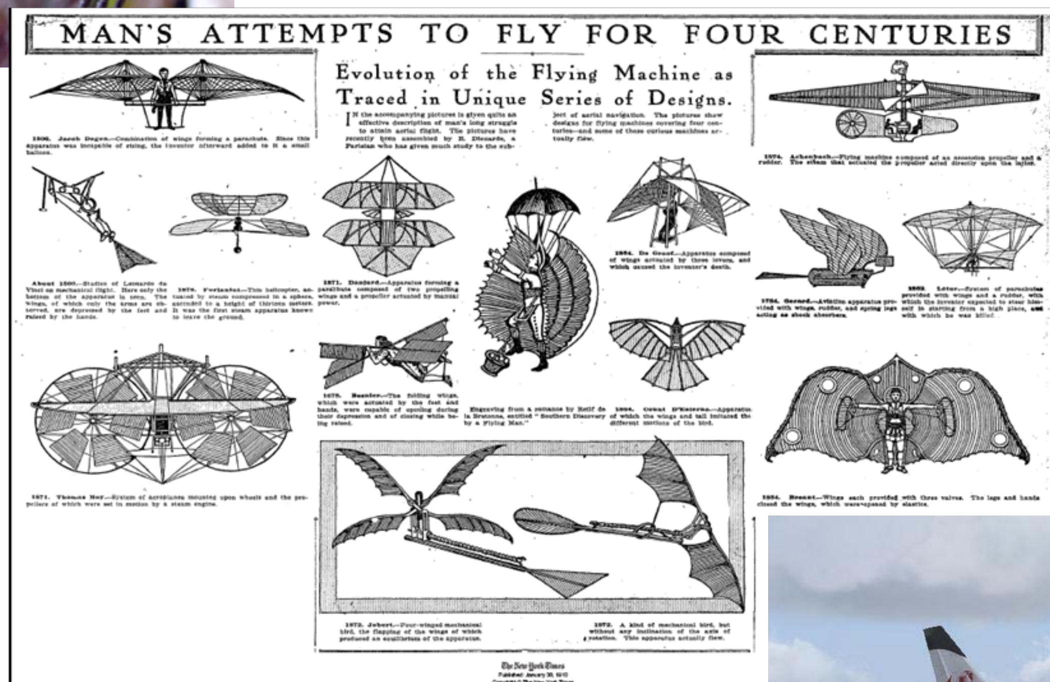
Building Systems on Nanoscales

Challenges (some):

- **Control of nano-object positioning and orientation**
- **Assembly of large scale systems/devices with designed architectures**
- **Assembly of finite size clusters**
- **Building hierarchical structures**
- **Dynamic (re-configurable, responsive, self-repaired…) systems?**



MAN'S ATTEMPTS TO FLY FOR FOUR CENTURIES

Evolution of the Flying Machine as Traced in Unique Series of Designs.

IN the accompanying pictures is given quite an effective description of man's long struggle to attain aerial flight. The pictures have recently been assembled by E. Dieuarde, a Parisian who has given much study to the subject of aerial navigation. The pictures show designs for flying machines covering four centuries—and some of these curious machines actually flew.

Outline

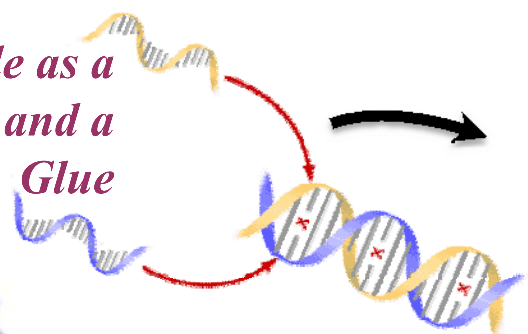
- Review (short) of approaches
- DNA mediated interactions in micro-and nanoscale systems
- DNA guided 3D Ordering
- Particles and DNA on surfaces
- Dynamically reconfigurable systems
- Cluster Assembly: building nano-”molecules”

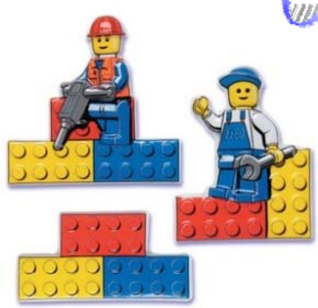
Building Materials on the Nanoscale

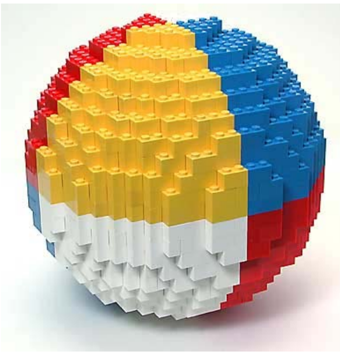
Biomimetic Solution? :
Using a nature's developed biological machinery to program how nano-blocks build materials by themselves.

Approach: Can we "program" nano-blocks to self-assemble in well organized structures?

Biomolecule as a Builder and a Glue





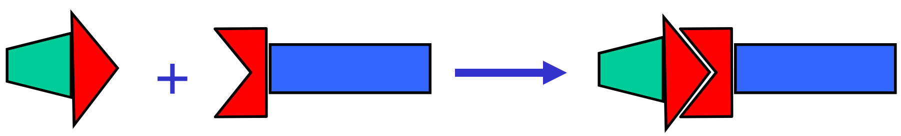


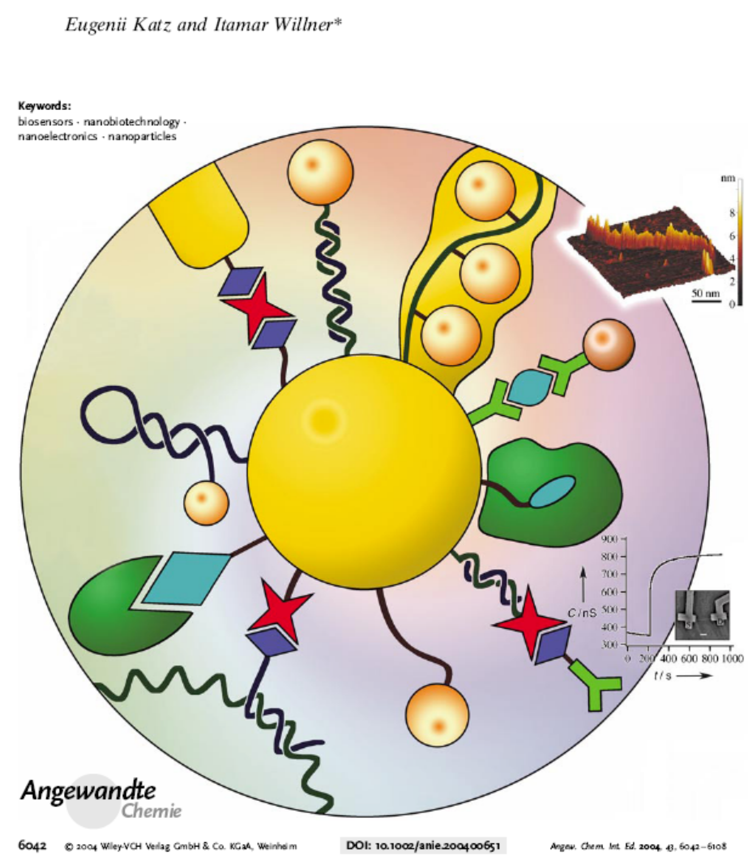
Bio-inspired Assembly

Bio-inspired Assembly: Why it is attractive?

To take advantage of the specific "key-lock" interactions for nano-object manipulation

recognition ***"key-lock"***





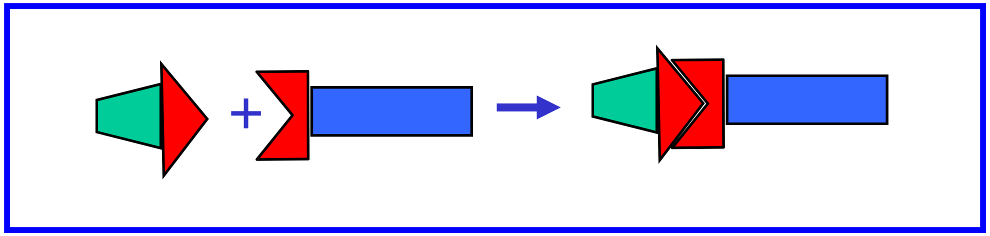
Some implementations for nanosystems:

DNA functionalized nanoparticles
(Mirkin, Alivasatos and others)

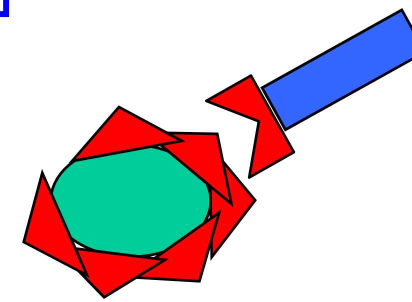
With DNA scaffolds
(Seeman, Hao and others)

With Proteins
(Willner, Matsui, Belcher, and others)

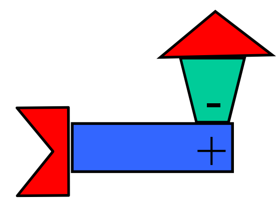
Bio-inspired Assembly



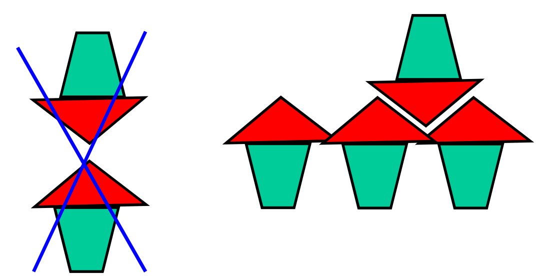
What has to be accounted?



• Biomolecules can behave differently in the bio-“crowded” and nano-confined environments

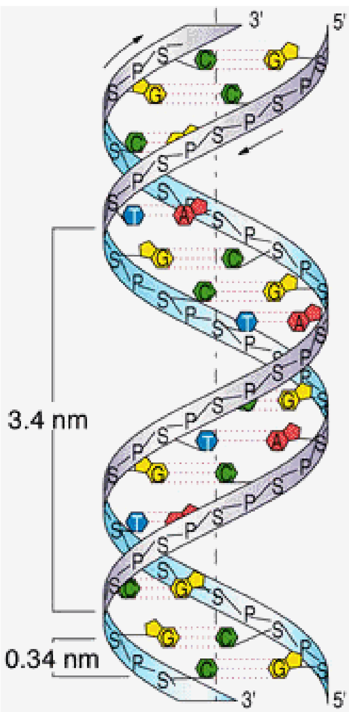


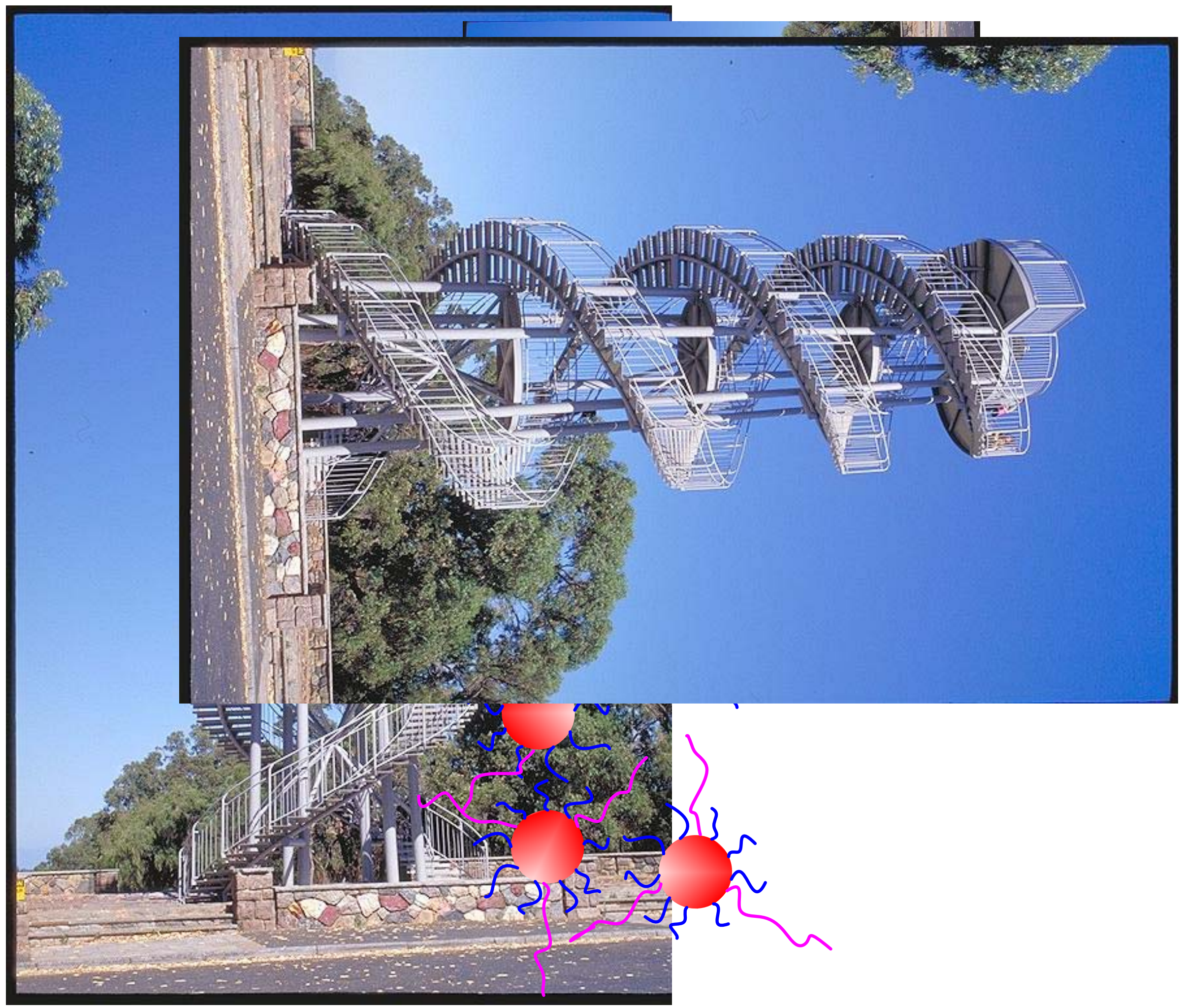
• The interplay between “key-lock” interaction and other interactions/effects. Can we regulate it?



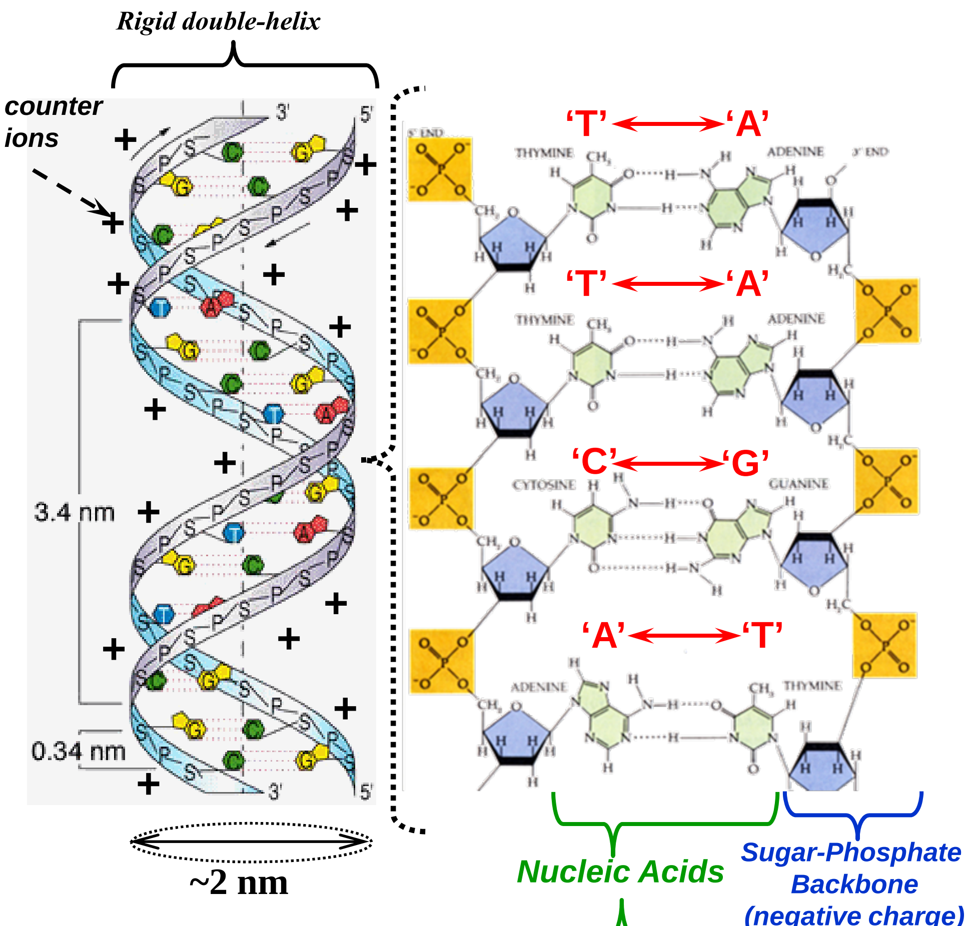
• Collective behavior of biomolecules might give rise to new effects and rich phase behavior of hybrid systems

• DNA provides an Information Storage in Biosystems
• Can be it used as a Structural Element in Nanosystems?





DNA - DEOXYRIBONUCLEIC ACID



Nucleic Acids
A: *Adenine*
T: *Thymine*
G: *Guanine*
C: *Cytosine*

Binding Strength Regulated by:
- Sequence (#G-C, #A-T pairs)
- Length (# of base pairs)
- Temperature & Ionic Strength

Potential Advantages of Using DNA & synthetic oligonucleotides in Nano-tech Applications:

Scalable
~ nm → μm

Tunable Interaction Strength
Hybridization Specificity

Structural Properties

Potentially "Green"
"Low cost," non-hazardous, aqueous

Biocompatibility
Biodiagnostics, Treatment

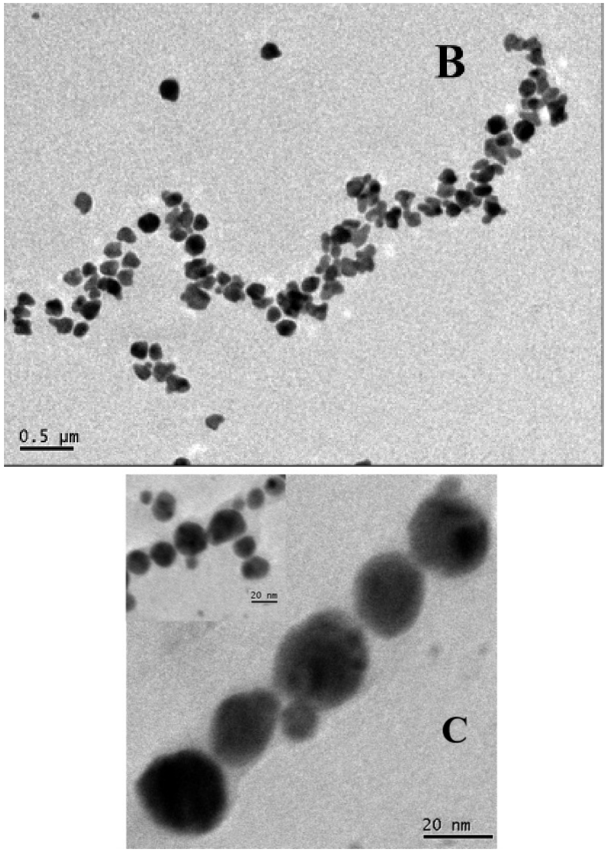
....

Interesting Materials Chemistry Platform:

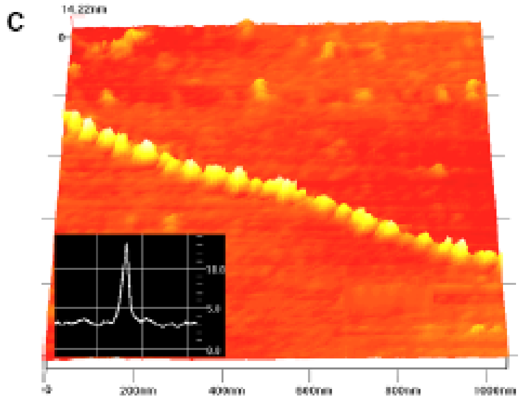
Extremely tunable:
Both chemically, and mechanically
Single strands flexible.
Double strands relatively rigid (persistence length ~50nm).

Highly Unique Assembly System:
Reversible

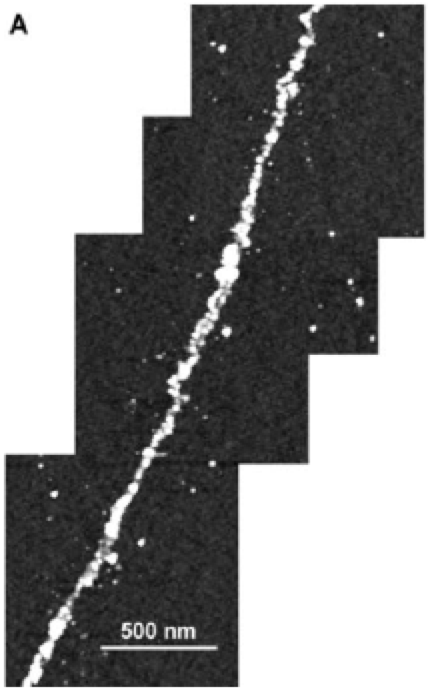
DNA as a template



Saraf, Langmuir,, 2007

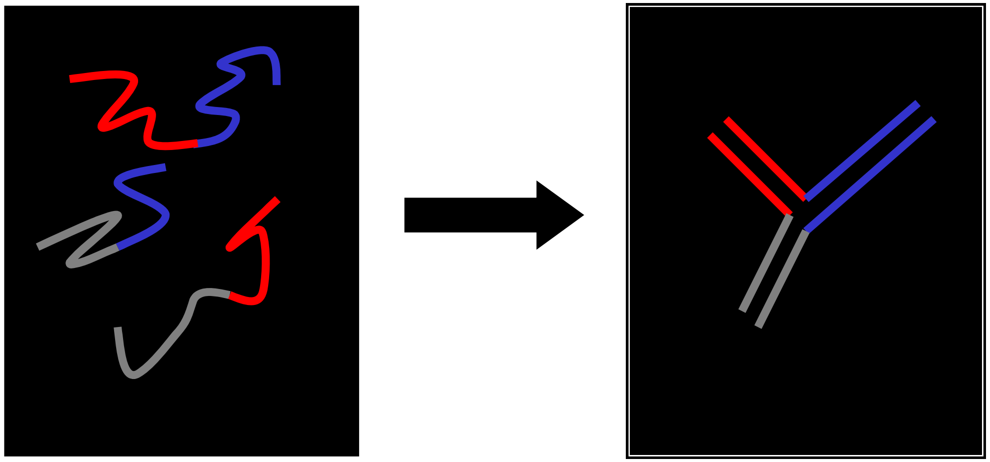


Gu, Nanotechnology 15, 2005



Woolley, ChemMat , 14,2004

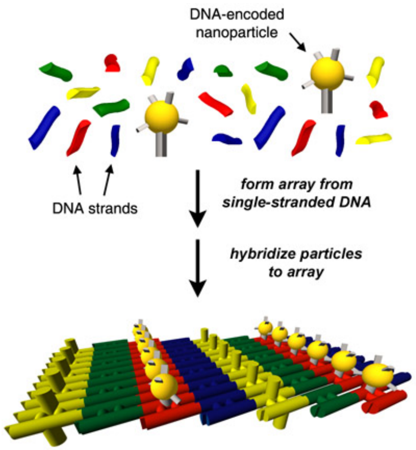
Branch Junctions

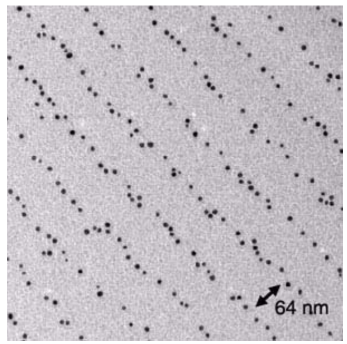


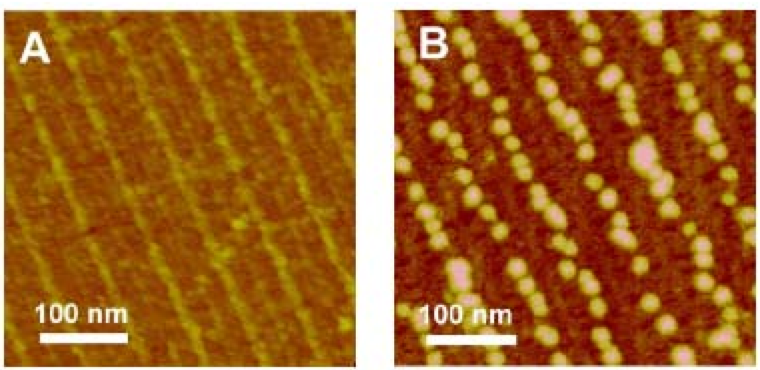
- Sequence programming can specify multi-armed junctions.
- Actual formation is very easy - just heat then slowly cool the strands.

Petrillo, M. L.; Newton, C. J.; Cunningham, R. P.; Ma, R. I.; Kallenbach, N. R. Seeman, N. C, *Biopolymers*, 27, 1337-1352 (1988)

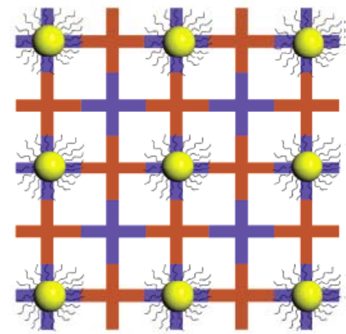
Nanoparticle positioning using DNA scaffolds

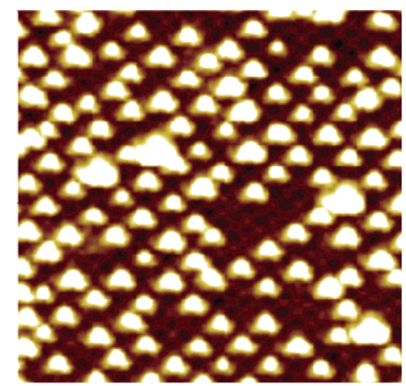






Seeman, Kiehl et al , NanoLett, 4, 2343, 2004





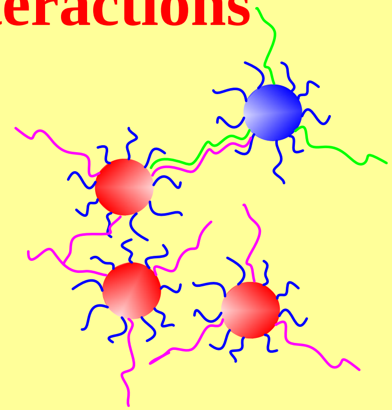
500x500 nm

Hao et al Nano Lett 2006

Systems with DNA Mediated Interactions

Encoded interactions

Binary systems

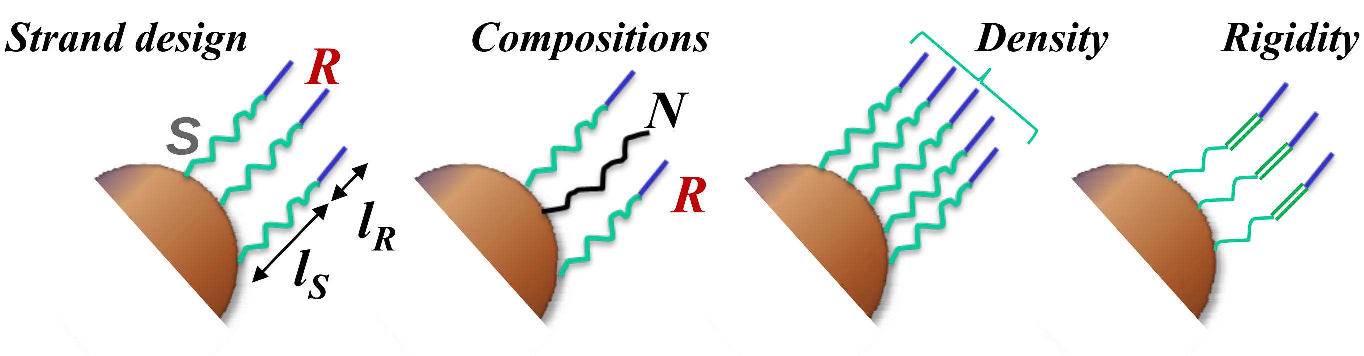


Interaction control

Addressability of interaction

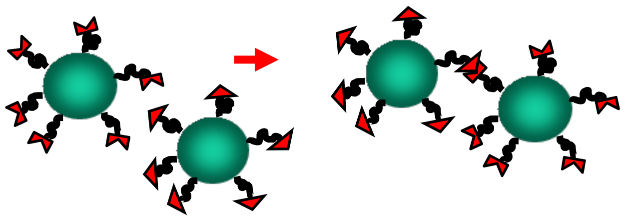
Structure control of Multicomponent systems

- A combination of physical interactions and addressability of particle/DNAs allow for tuning interparticle potential

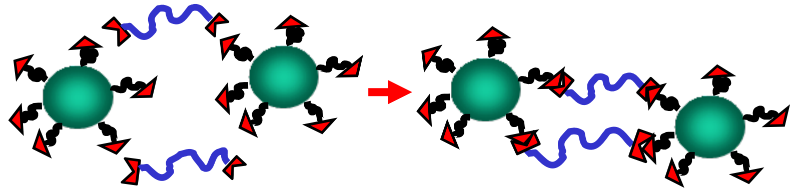


Typical DNA mediated particle assembly

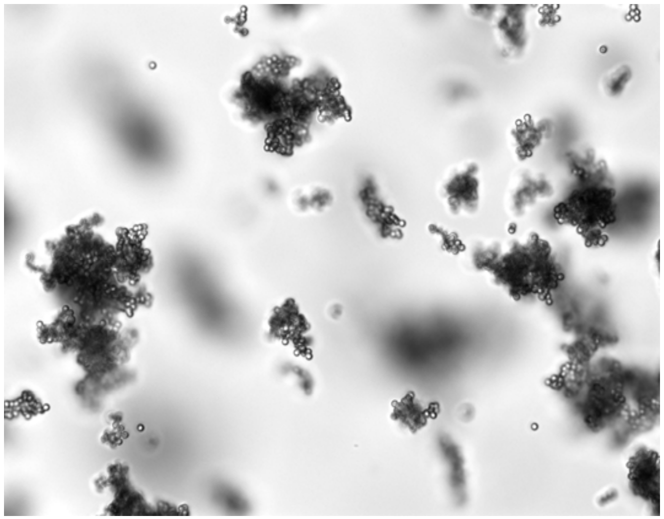
Direct particle hybridization



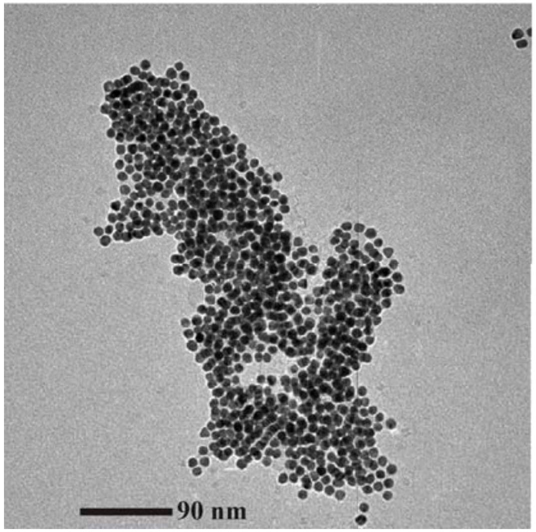
Linker induced hybridization



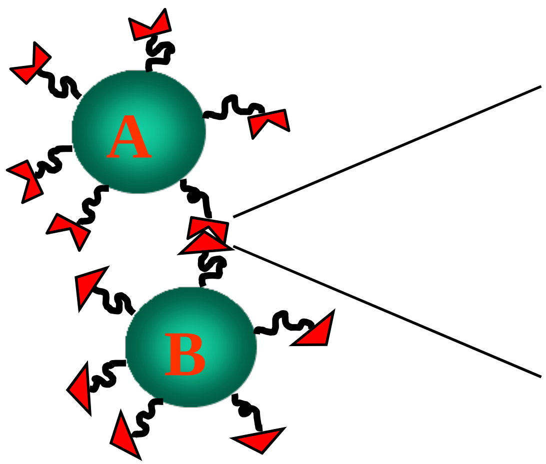
Micron-sized Colloids

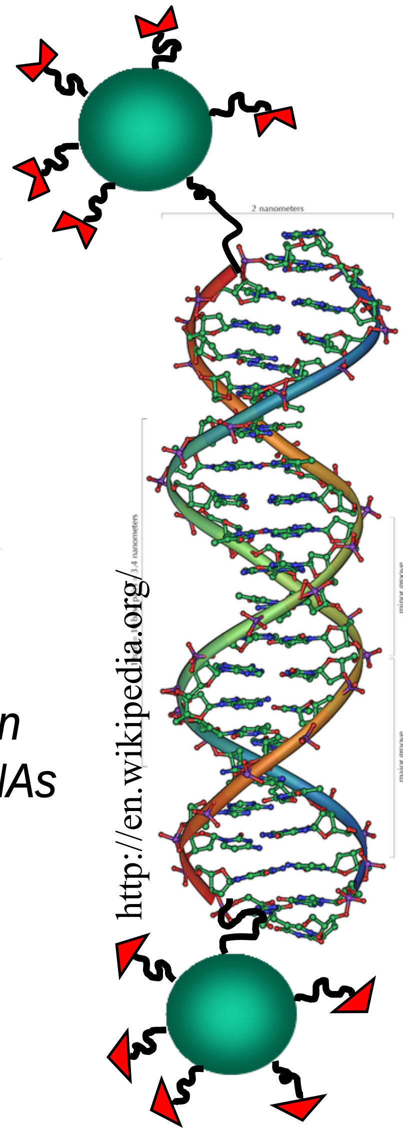


Nano-sized Particles



DNA-Mediated Self-Assembly: colloidal system

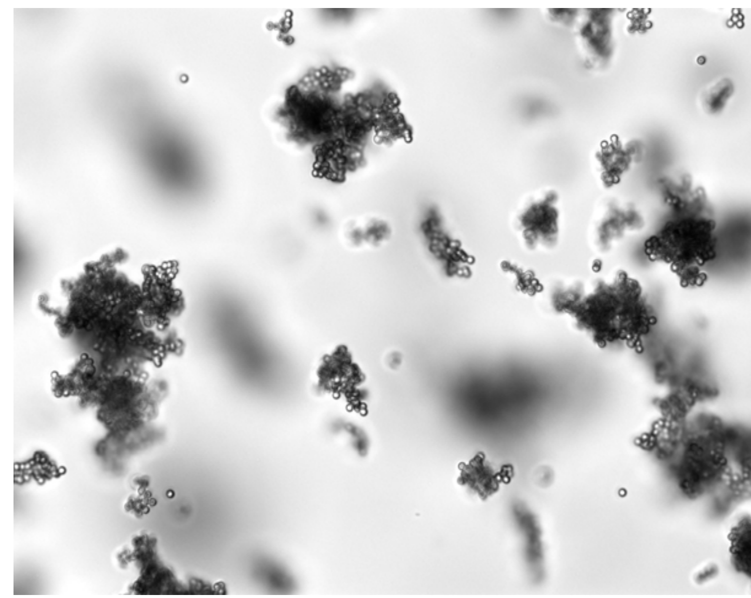




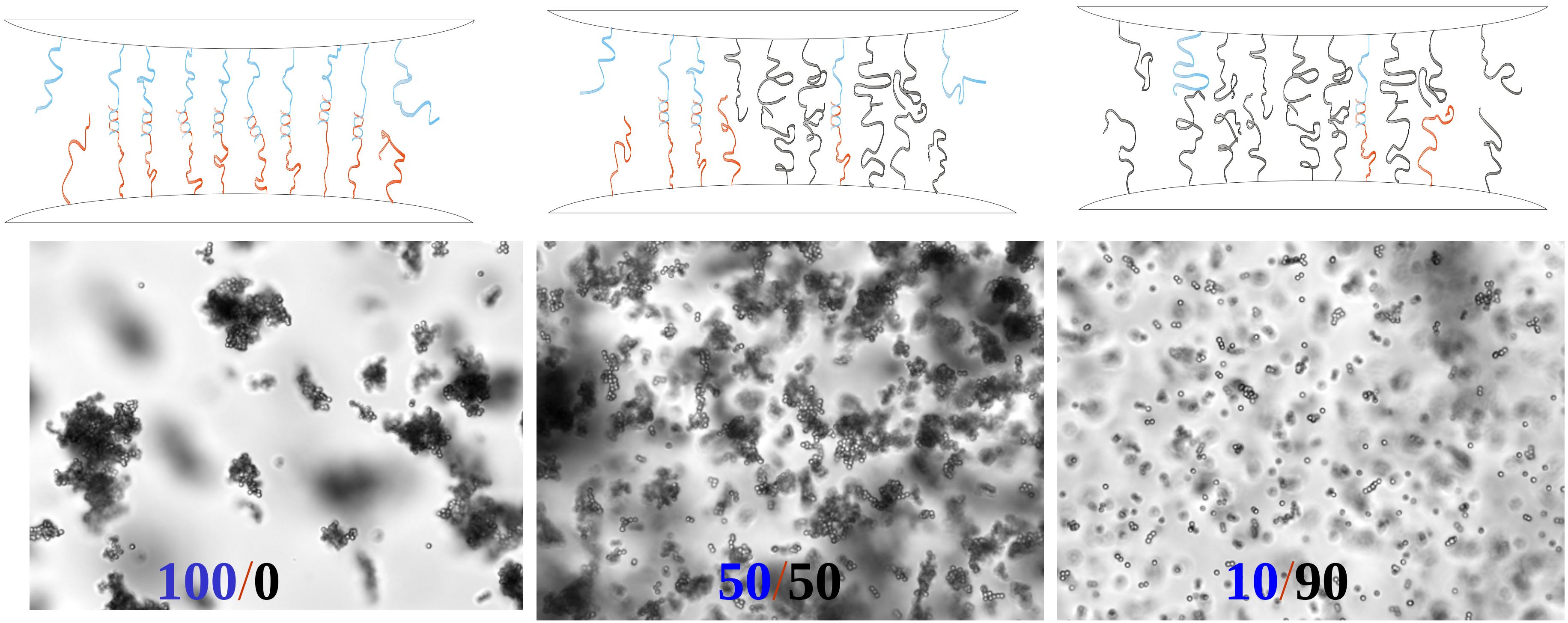
Hybridization between complementary ssDNAs

Measured DNA coverage:
300,000 DNA/particle,
~$40nm^2$ per DNA, ~R_g^2

Aggregation formation



Tuning the morphology of assembling through the “neutral” DNA

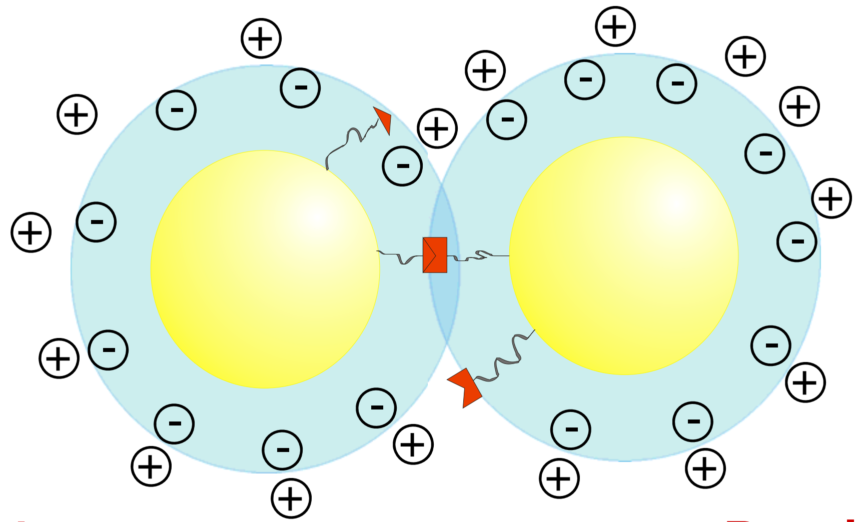


complementary/non-compl. ss DNA concentration

Optical microscopy images after 24 hours of mixing

D. Nykypanchuk, M. Maye, D. Van der Lelie, O. Gang, Langmuir (2007), 23(11):6305

Mechanism of Interactions



Attraction:
Van der Waals (*vdw*) interactions and
DNA hybridization (*hbr*) energies

Repulsion:
Electrostatic (*el*) interactions and
osmotic (*osm*) pressure

$\Delta E_{attr}=\Delta E_{vdw}+\Delta E_{hbr}$

$\Delta E_{attr}=\Delta E_{vdw}+\Delta E_{hbr}$

exchange
“linker” with
“neutral”

$\Delta E_{rpl}=\Delta E_{el}+\Delta E_{osm}$

$\Delta E_{rpl}=\Delta E_{el}+\Delta E_{osm}$

$\Delta E_{osm} \sim C \ldots C^2$

$\Delta E_{hbr} \sim N$

~ 35 kT/link

Can be balanced

$P_{osm} \sim 10^0$ atm
$E_{osm} \sim$ few kT/DNA

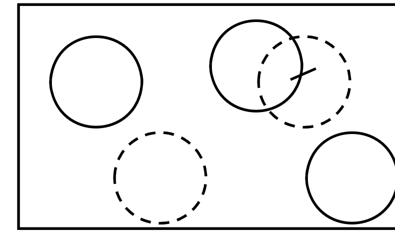
Energy profiles

attraction

$$E_a(d,f) = E_h \int_0^{R(d)} 2\pi r f \rho_0 P(d,r,f)\,dr + E_w(d)$$

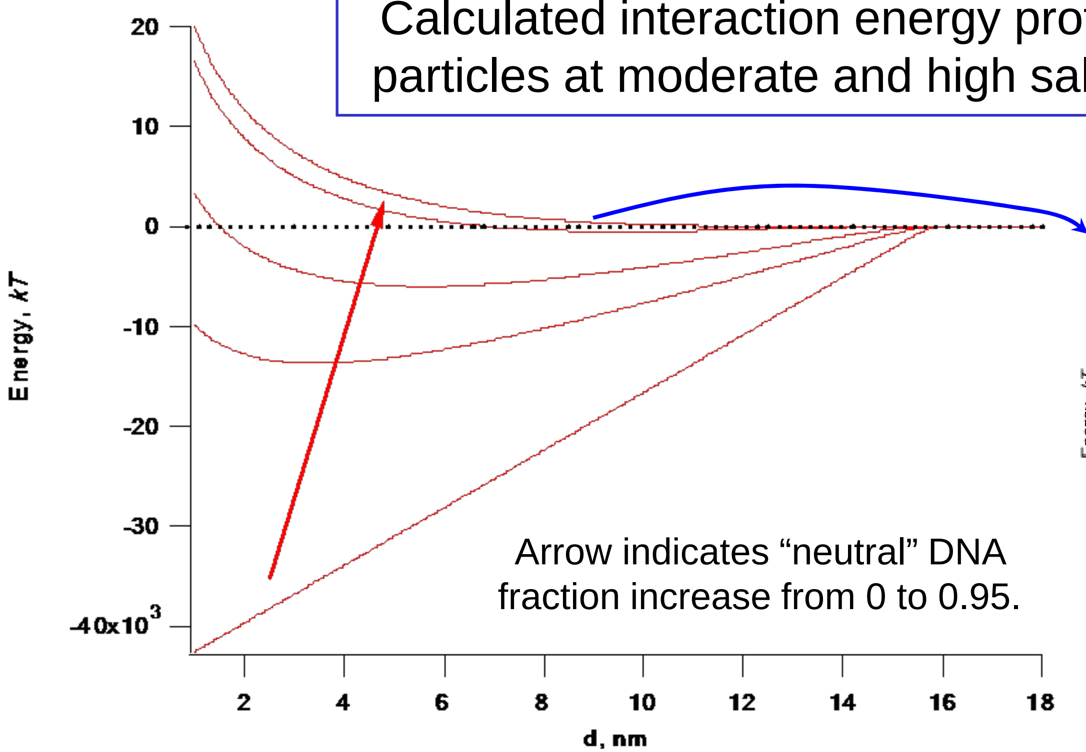
repulsion

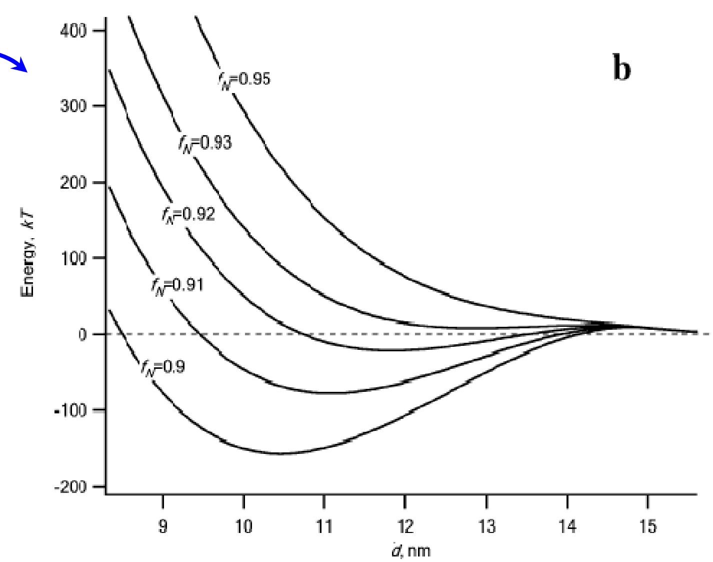
$$E_r(d,f) = \int_0^{R} 2\pi r \rho_0 E_{ou}(d)(1 - fP(d,r,f))\,dr + E_{oh}(d,f) + E_{el}(d - 2b_0)$$



P (d,r,f) – the probability of overlap: $P(d,r,f) = \left(1 - \left(\left(1 - \pi a^2(d,r) f \rho_0\right) \exp\left(\frac{-3\pi a^2(d,r) f \rho_0}{1 - 2\sqrt{3} a^2(d,r) f \rho_0}\right)\right)\right)$

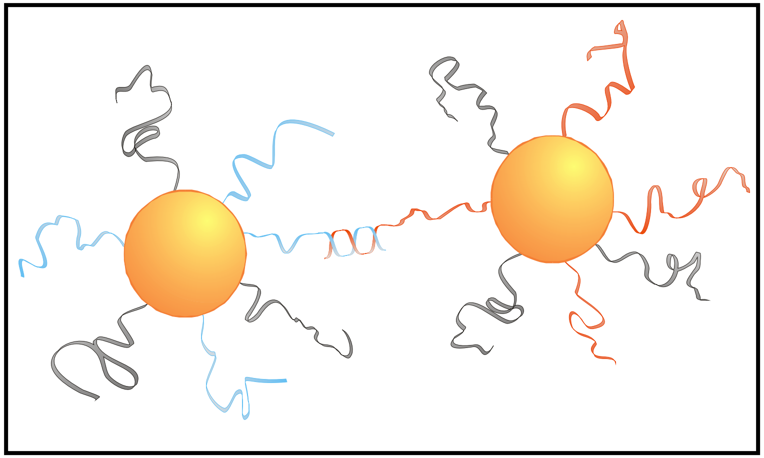
Calculated interaction energy profiles for 1.9mm particles at moderate and high salt concentration





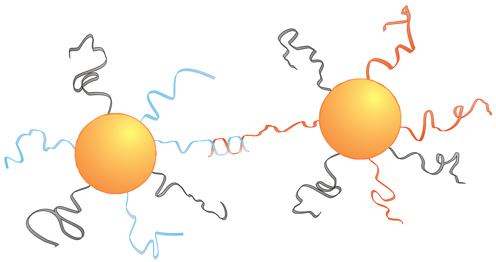
D. Nykypanchuk, M. Maye, D. Van der Lelie, O. Gang, Langmuir (2007), 23(11):6305

Nanoscale

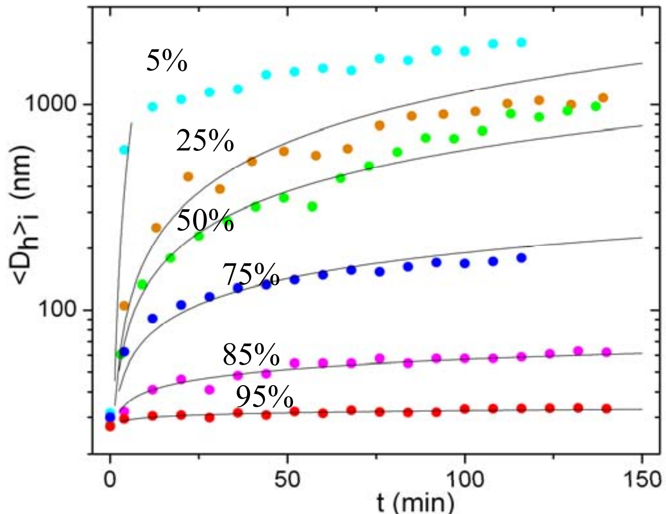


- DNA is comparable with particle size- “long-range” interactions
- Small number of DNA per particles (1 to 10^2). Can we average interactions?
- How to probe structure?

Tailoring interparticle interactions with DNA

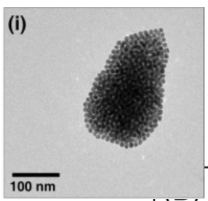


Assembly Kinetics DLS

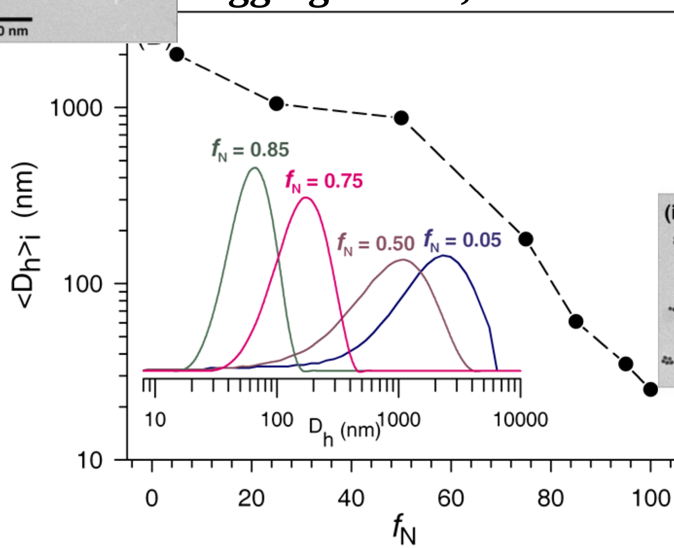


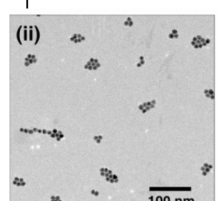
$$\langle D_h \rangle_i \sim (t/\tau)^{\gamma}$$

τ characteristic time, ~ doublet formation, increases from fraction of minute to tens minutes with the fraction of “neutral” DNA, f_N from 5% to 95%



Aggregate size, DLS after ~120 min

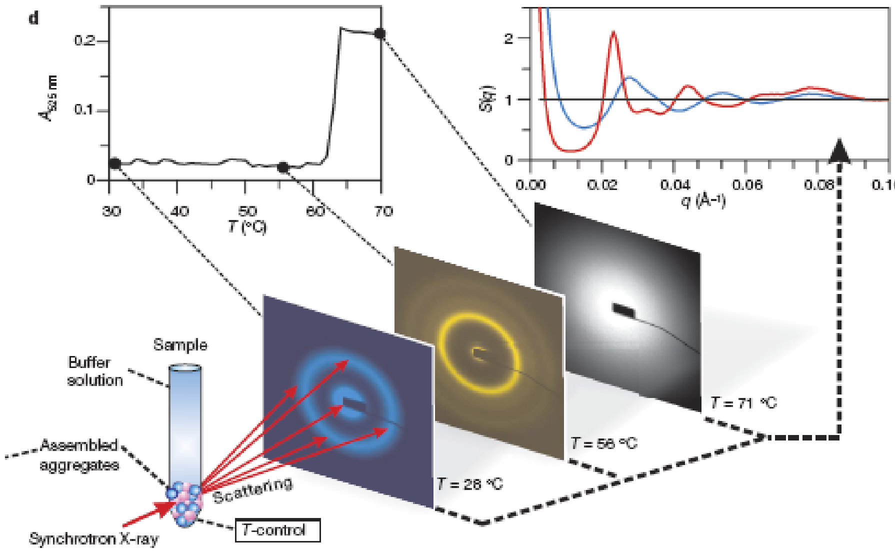




The transition from strongly aggregating regime to stabilization is observed with f_N increase

M.M. Maye, D. Nykypanchuk, D. van der Lelie, O. Gang, *Small* 3, 1678 (2007)

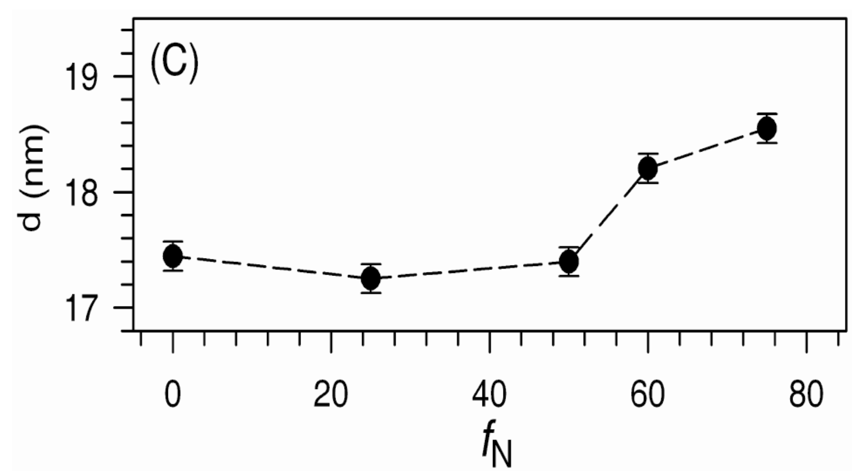
Small Angle X-Ray Scattering (SAXS)



d increase from ~17.3 nm to 18.6 nm at f_N~50% suggests:

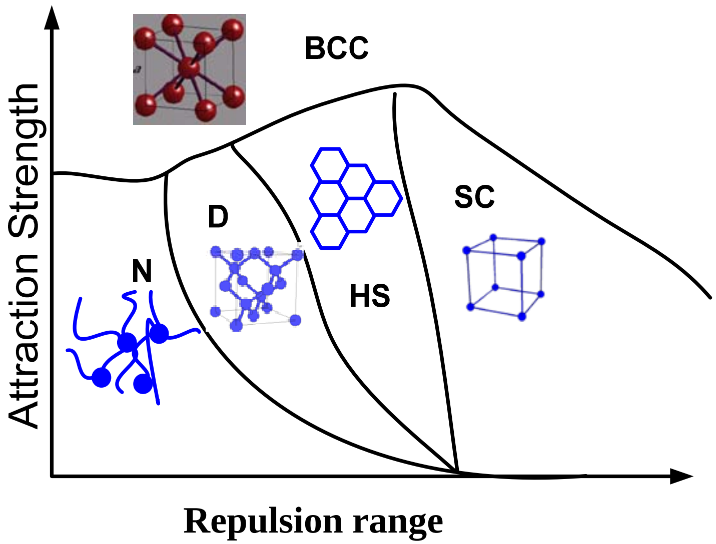
• kinetic effects might be responsible for the slower assembly of aggregates at f_N<0.5,

•stronger repulsion component in the interparticle potential results in greater *d* at f_N>0.5

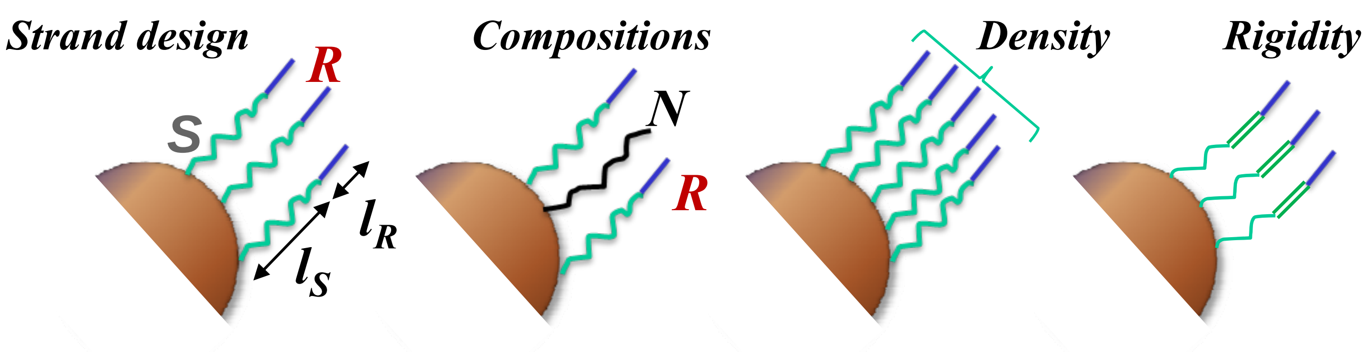


DNA-guided 3D Ordering of Nanoparticles

• A combination of physical interactions and addressability of particle/DNAs allow for tuning interparticle potential

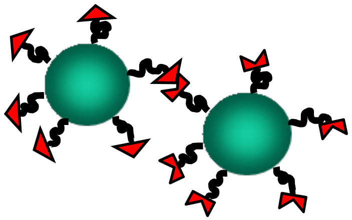


A. V. Tkachenko, PRL 89, 148303 (2002)

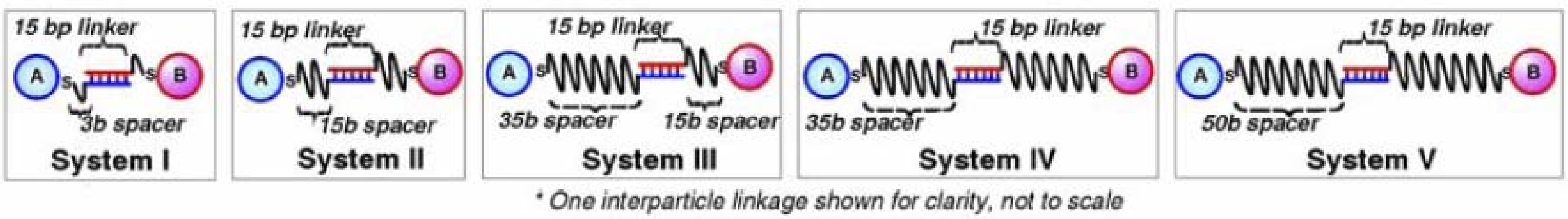


DNA-guided 3D Ordering of Nanoparticles

- **DNA-based approach provides a broad range of methods for tuning an inter-particle potential ***
- **Inter-particle potential is tuned via ss-DNA spacer, recognition fragment is constant**



Softer potential



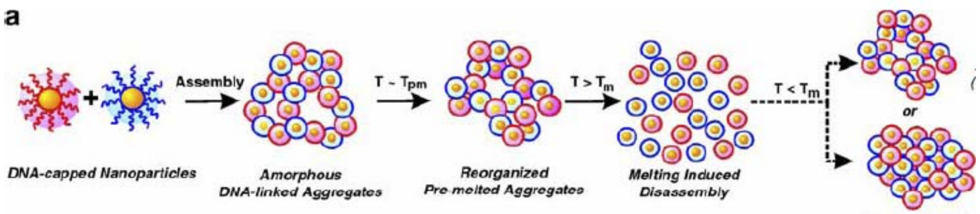
Attraction: $E_a \sim N_a$

Repulsion: $E_r \sim N^{3/5}/(N^{3/5} - cN_a)$

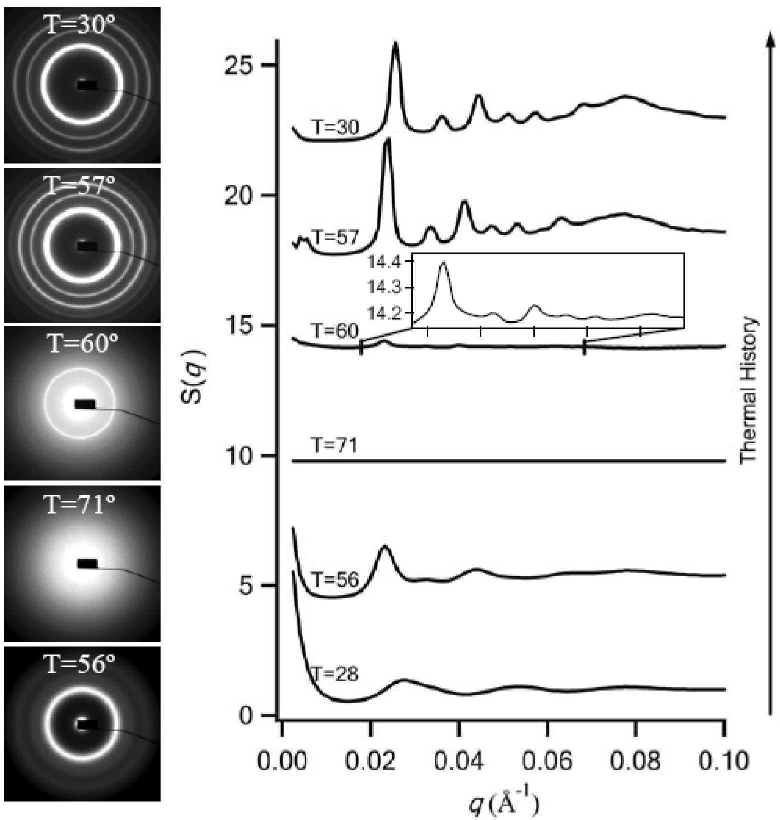
c is defined by persistence length and surface density

repulsion range $d_r \sim N^{3/5}$

DNA-guided 3D Ordering of Nanoparticles



- Even for the “right” potential assembly is locked in disordered metastable state



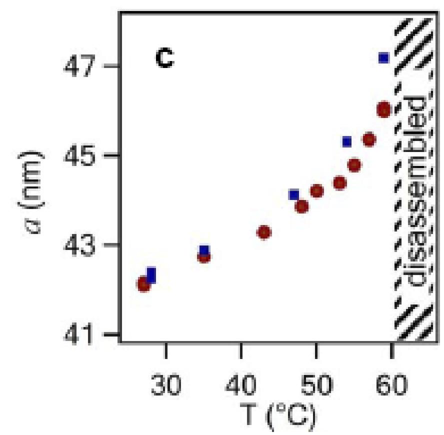
Ordered

Order onset

Molten

Reorganization at $T<T_m$

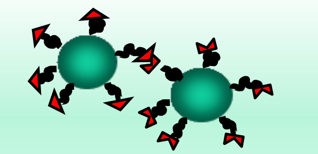
Disordered, as assembled



D. Nykypanchuk, M. Maye, D. Van der Lelie, and O. Gang, *Nature, 451, 549 (2008)*

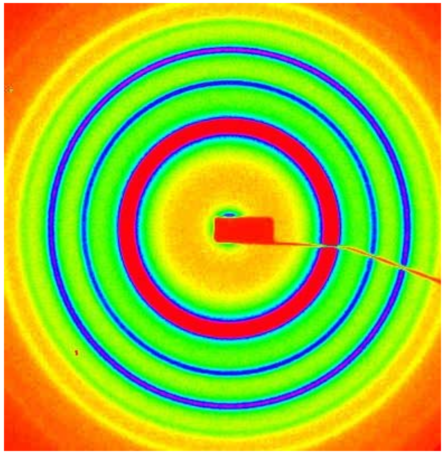
DNA-guided 3D Ordering of Nanoparticles

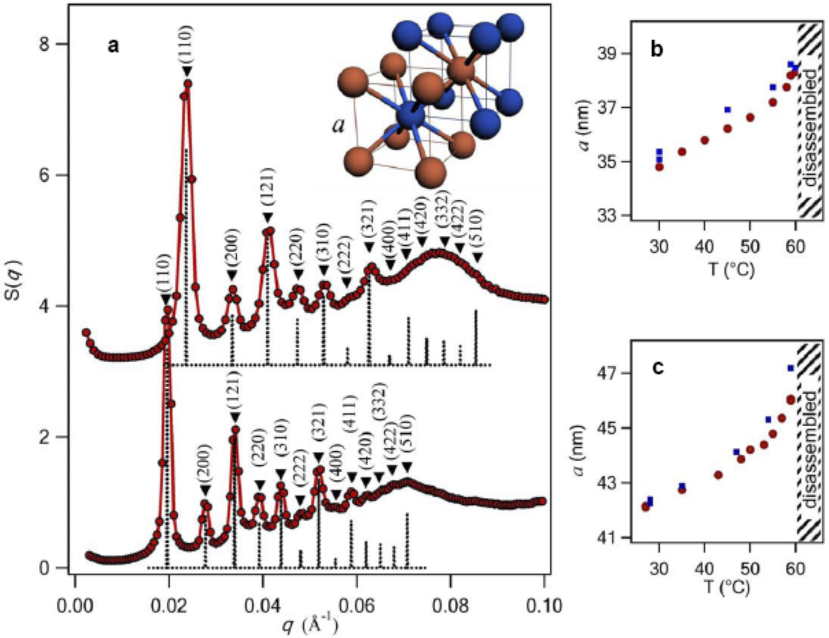
- BCC structure, resolution limited diffraction peaks correlation length ~ micron
- Crystal is formed despite irregularities of particle sizes and number of DNA per particle
- Remarkably open structure: Nanoparticles and DNA occupy ~3-4% and 6-8% volume respectfully
- Generic approach: various types of particles can be incorporated



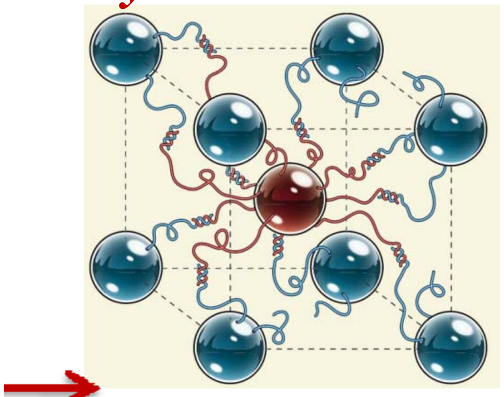
Direct particles hybridization

SAXS image





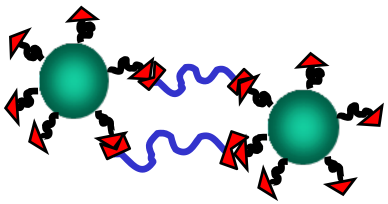
body centered cubic

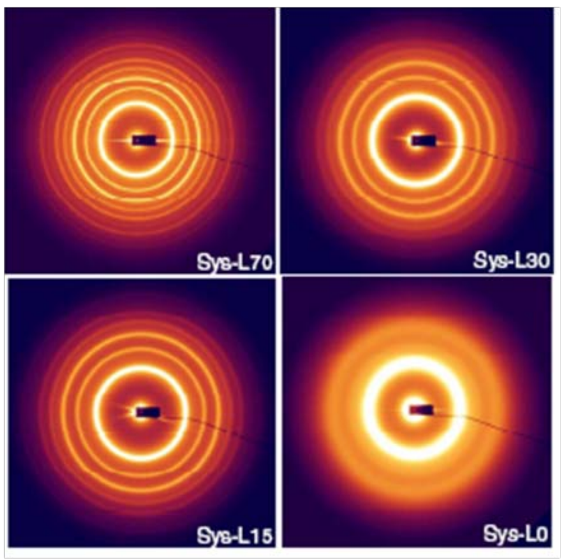


Nature 451 (2008), J. Crocker, News & Views

D. Nykypanchuk, M. Maye, D. Van der Lelie, and O. Gang, ***Nature, 451, 549 (2008)***

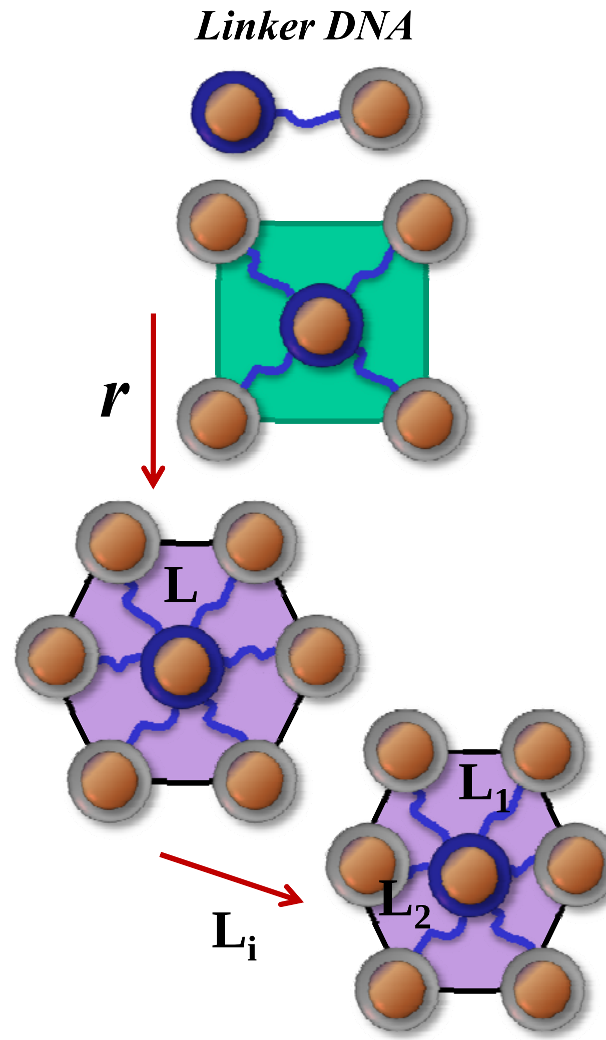
Assembly via DNA-Linkers





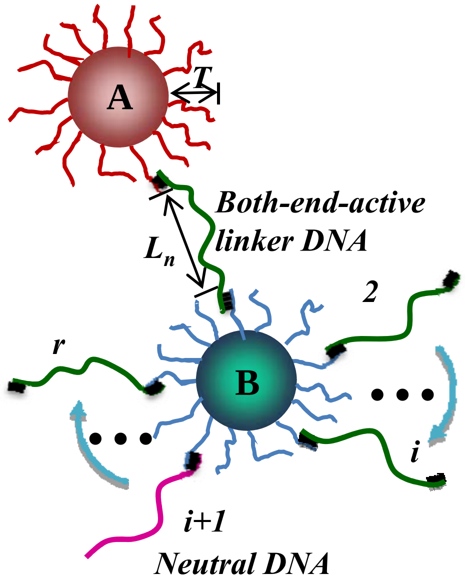
• Linker length L_n determines "softness" of the interactions,
• Crystalline (bcc) phases are observed

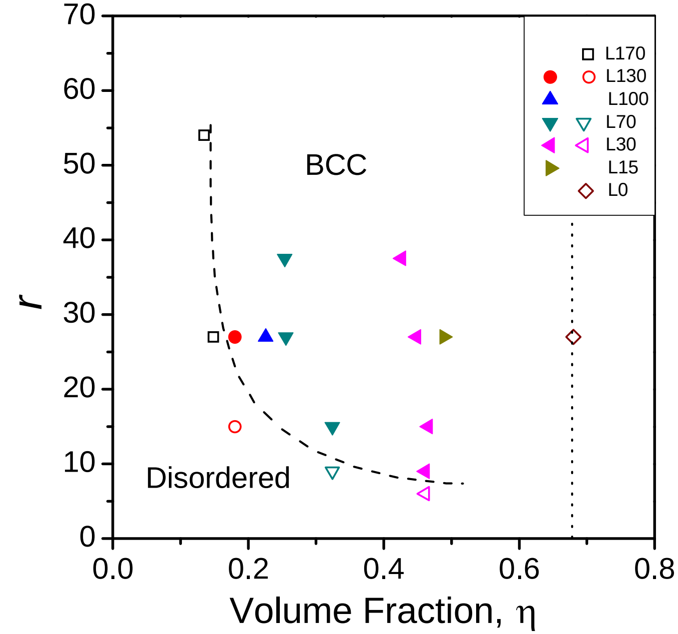
- **Relative concentration *r* of DNA linkers vs. particle has a dramatic effect on phase formation.**
- **How coordination number, controlled by *r*, influence a phase formation, dependence on linker length ?**
- **Linker with more than one length:** ***Distance Encoded phase formation***

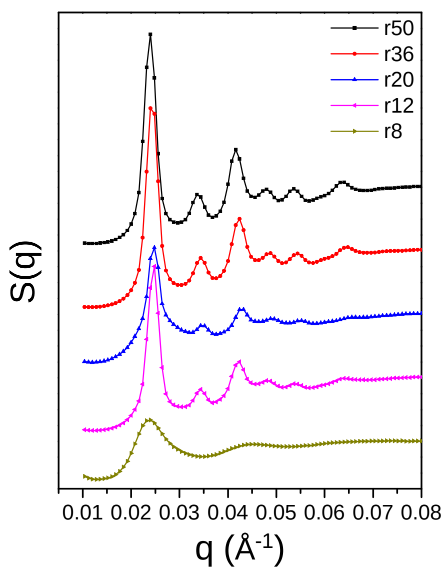


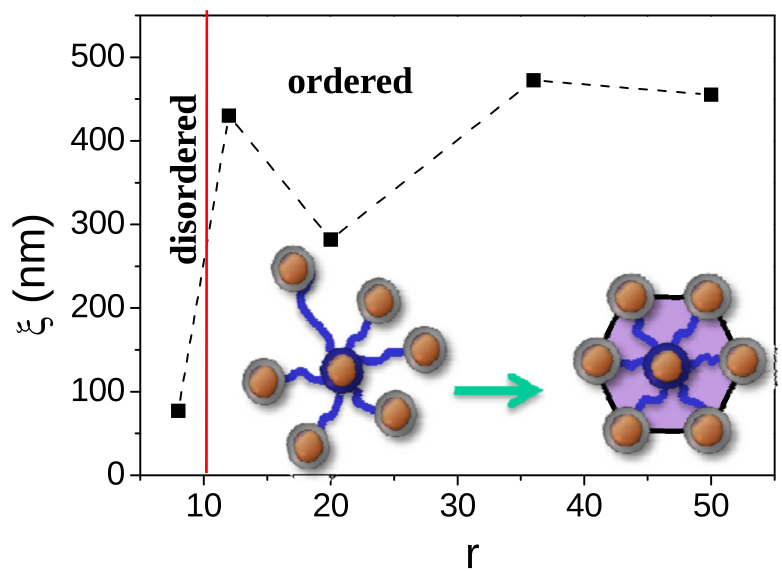
H. Xiong, D. Van der Lelie, and O. Gang, ***Jour. Amer. Chem. Soc., 130 (8), 2442 (2008)***

DNA Linker Mediated Assembly



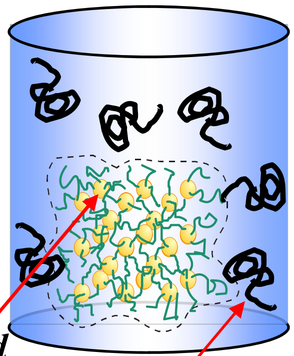


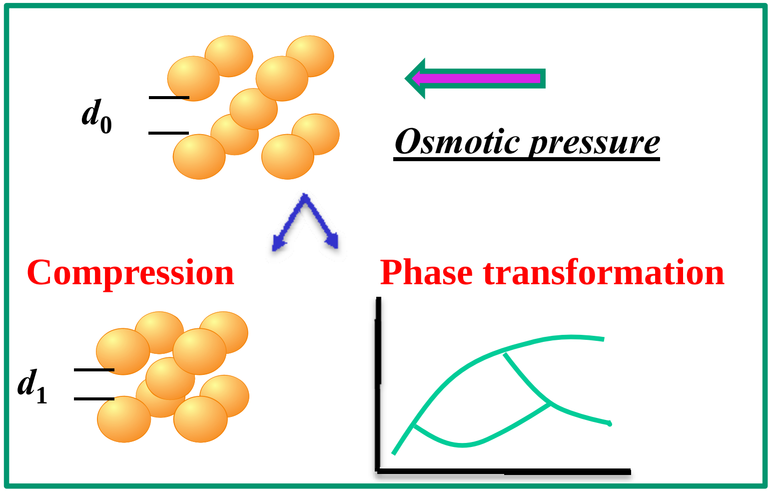




H. Xiong, D.van der Lelie and O. Gang, *(2008)*

Elastic properties of DNA Mediated Nanoparticles Assemblies

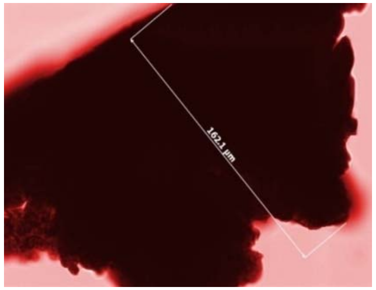




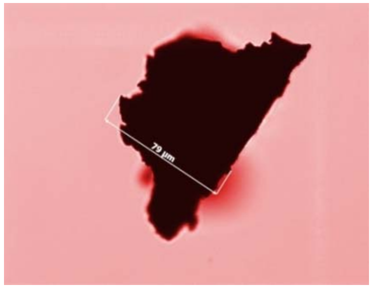
Pressure can be controlled in the range from 0 to ~30 atm by changing the concentration of polymer (PEG, 35k)

- How elastic properties of assemblies depend on properties of biomolecular linkers and degree of order?
- Phase transition under the pressure condition

Optical image of DNA/NP polycrystal



0% PEG



35% PEG

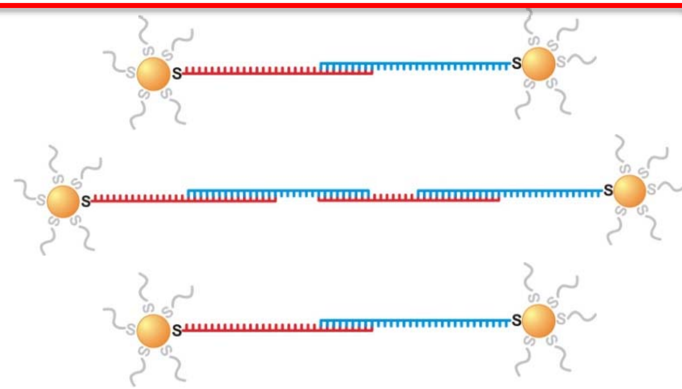
D. Nykypanchuk, M. Maye, O. Gang (2008)

Assemblies under Osmotic Stress

I

II

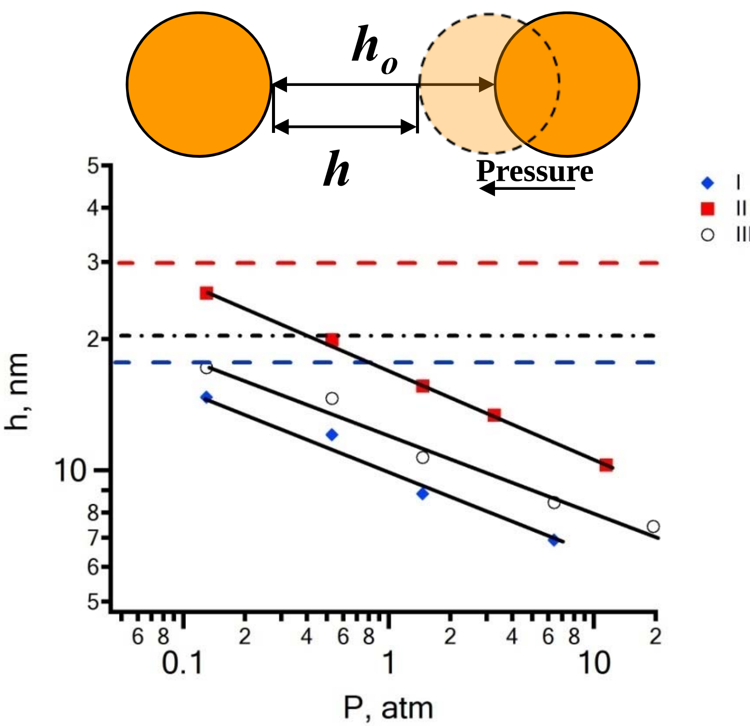
III

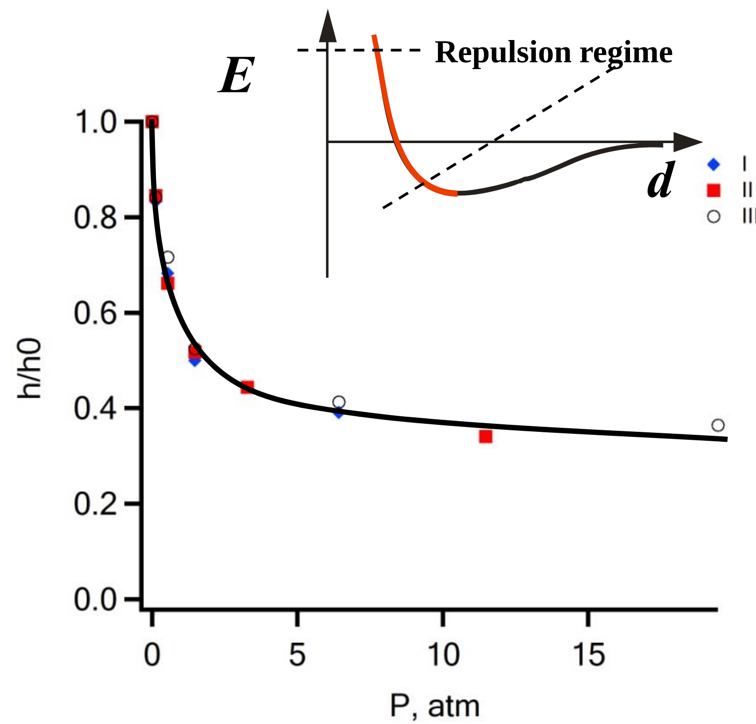


ss-DNA - 76 b; ds-DNA – 12 bp

ss-DNA - 70 b; ds-DNA – 65 bp

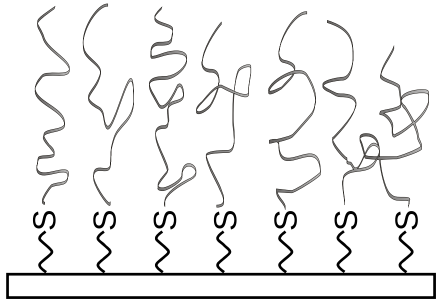
ss-DNA - 80 b; ds-DNA – 10 bp

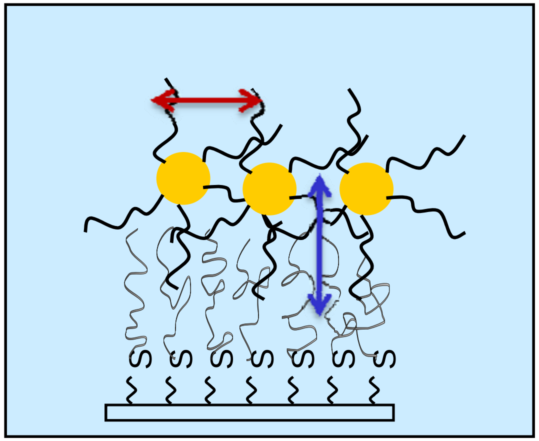




Repulsion is controlled by elastic properties of the chain

DNA Directed Assembly of Nanoparticles on Surface

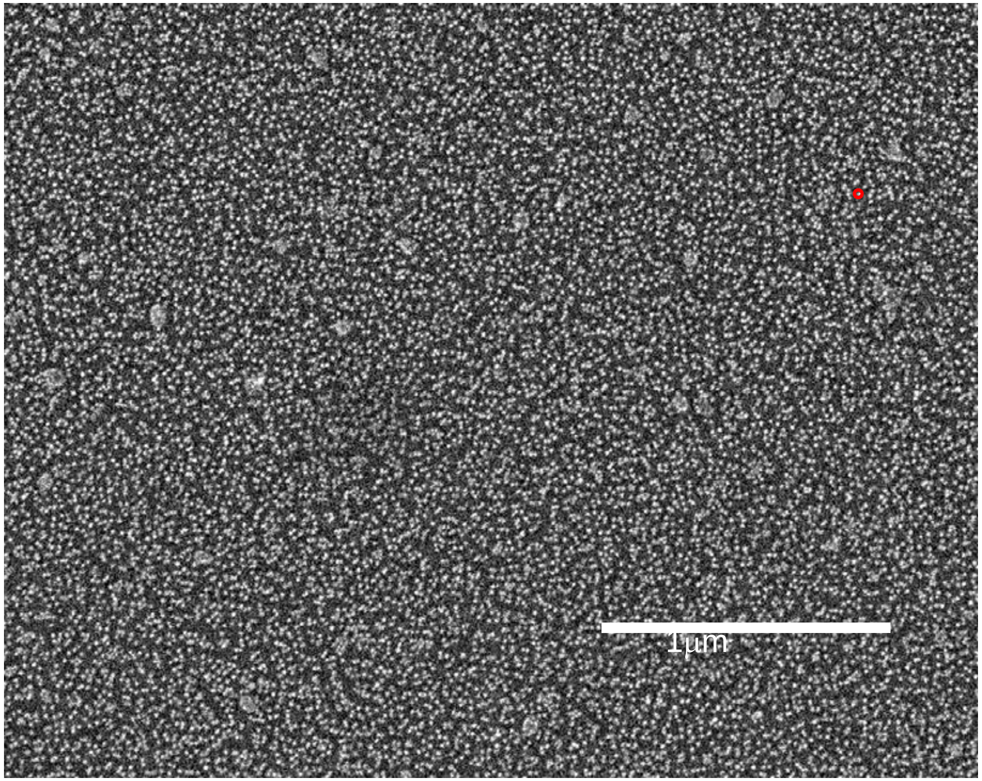




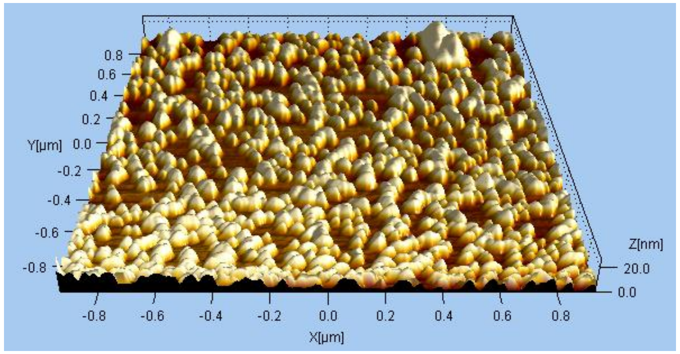
- Assembling of DNA functionalized nanoparticles on surfaces due to hybridization with surface grafted DNA
- 2D phases: similar to 3D systems, DNA/shell design principles can be applied to 2D system to regulate of surface-particle and particle-particle interactions

Imaging particles on the surface: EM and AFM

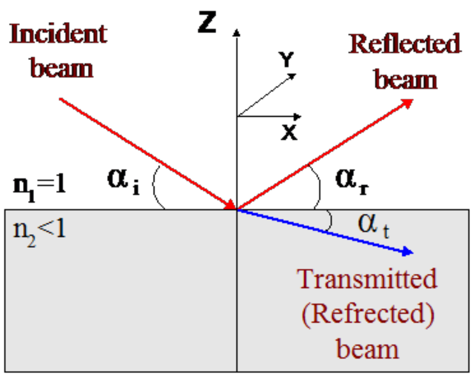
SEM image of gold nanoparticles immobilized on silicon surface via DNA linkage



AFM image and profile analysis after partial particle removal

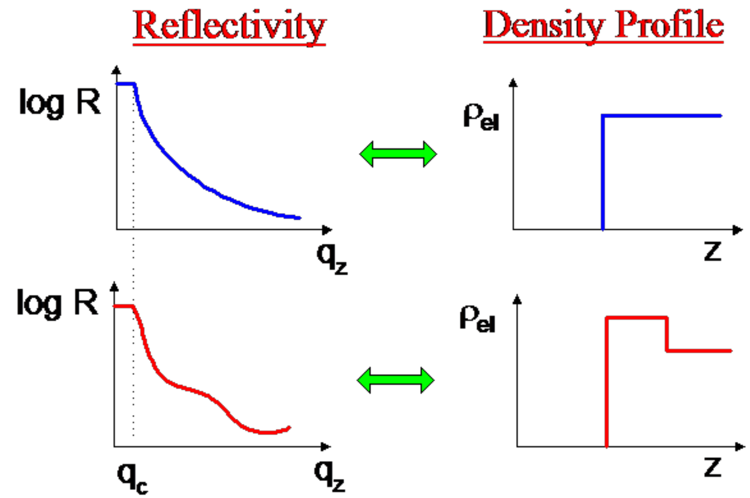


X-Ray Reflectivity ->> *structure normal to the surface*



Fresnel Reflectivity

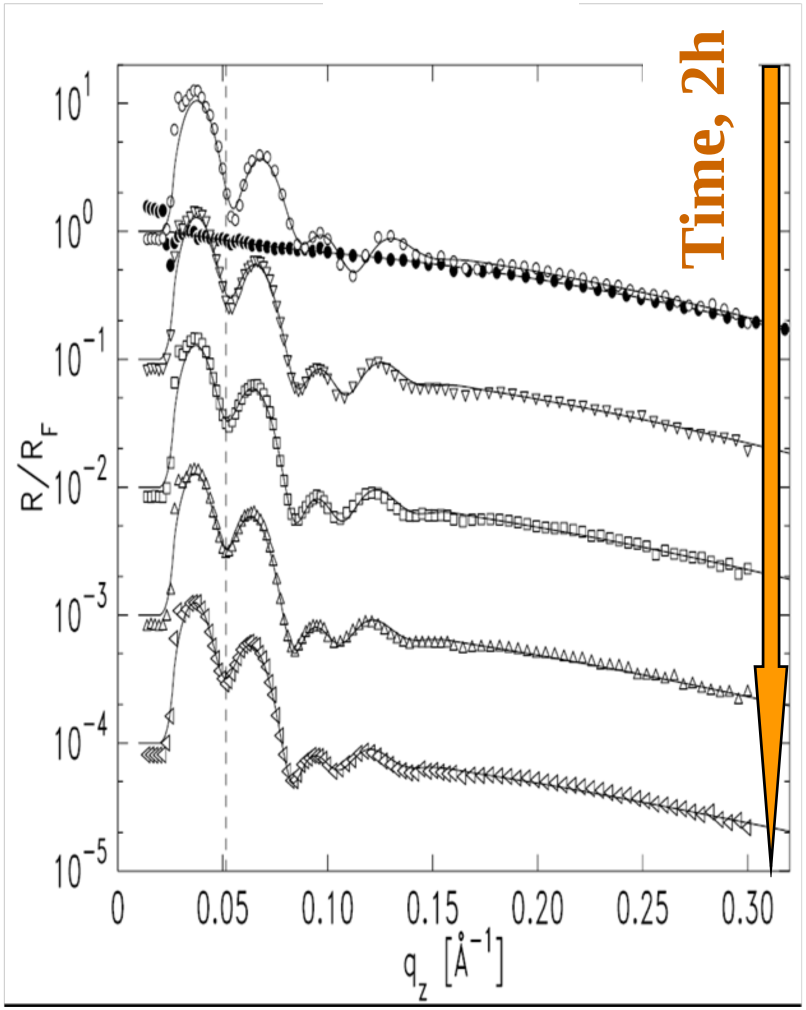
$$R_F(q_z) = \left| \frac{q_z - \sqrt{q_z^2 - q_c^2}}{q_z + \sqrt{q_z^2 - q_c^2}} \right|^2$$

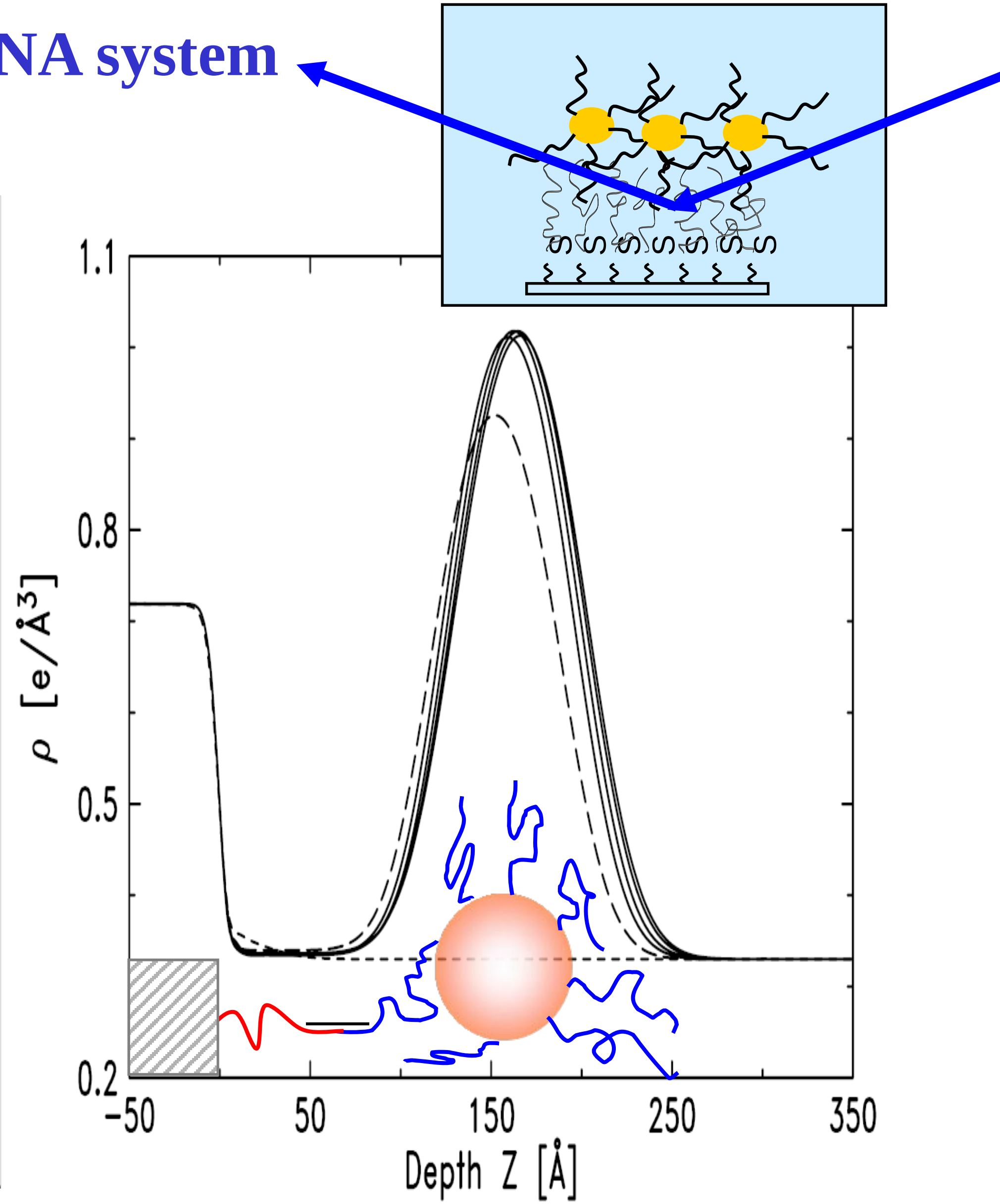


$$R(q_z) = R_F(q_z) \left| \Phi(q_z) \right|^2 \exp(-q_z^2 \sigma_{eff}^2)$$

- XR: low incident angles (<5°) -relatively large surface areas
- XR: Electron density profile normal to the surface
- Dynamical range of profile measurements: thickness 0.1- hundred nm, relative contrast ~ few %

Structure of 2D nanoparticle/DNA system

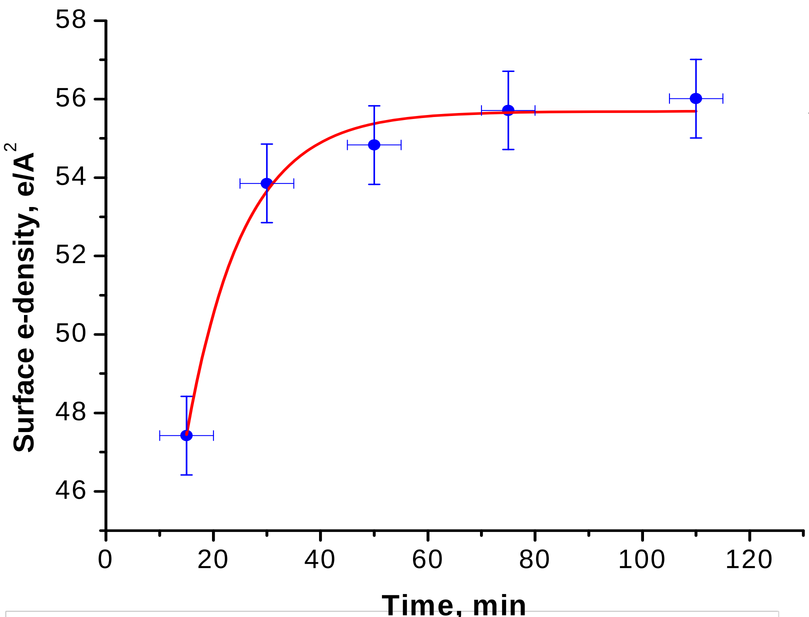




High energy (19keV) X-ray probes normal surface structure of NP/DNA system in-situ, at liquid-solid interface

O. Gang, D. Nykypanchuk, M.M. Maye (2007)

Kinetics of NP Adsorption/Hybridization



Coverage time dependence:

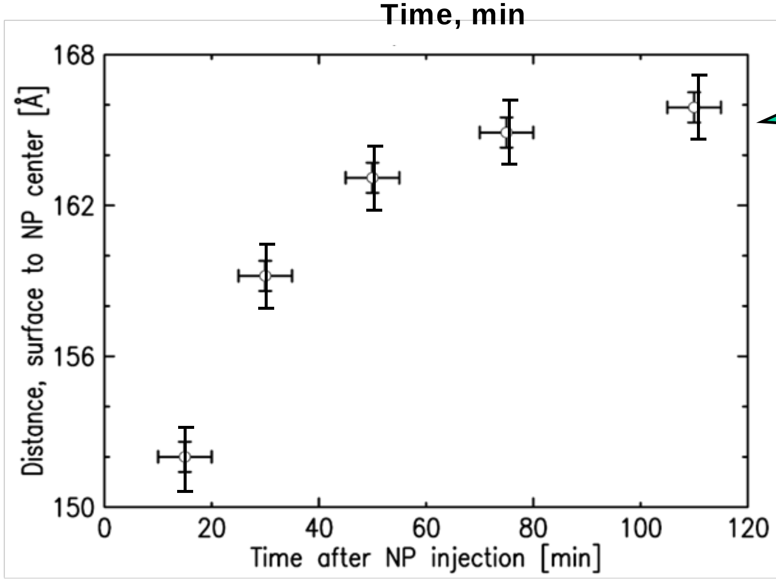
$X(t) = X_{eq}[1-\exp(-t/\tau)]$

$\tau^{-1} = k_h c$ for $k_h >> k_d$

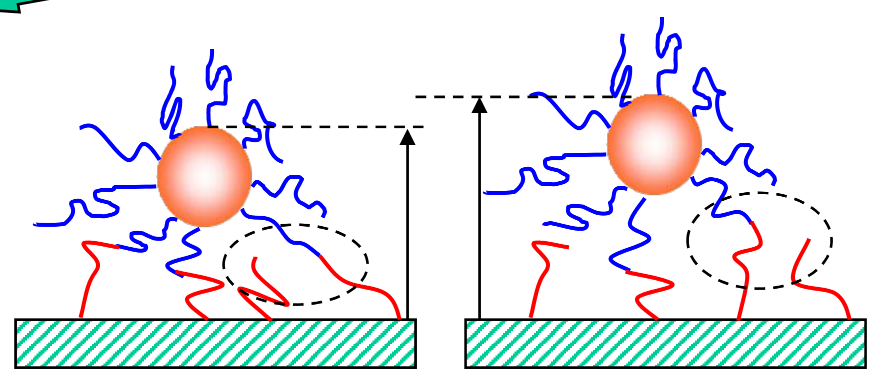
k_d and k_h - hybridization and denaturation rate constants at the surface

Observed $\boldsymbol{\tau}$ **= 643 s** $\rightarrow k_h \sim 1.5\ 10^6\ M^{-1}\ s^{-1}$

(comparable to DNA micro-arrays, $10^6\ M^{-1}\ s^{-1}$)

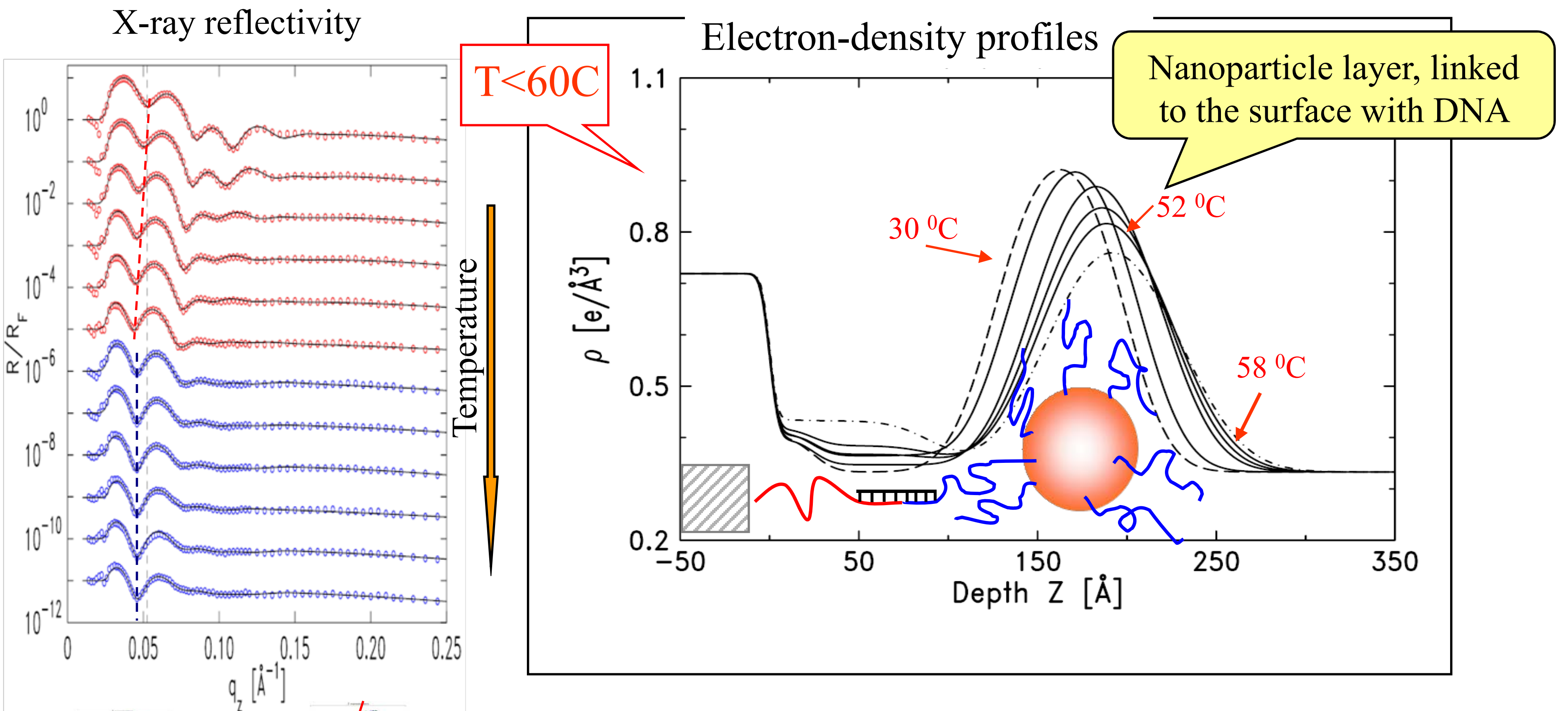


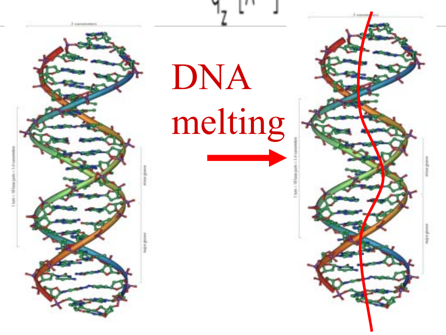
Position Relaxation



O. Gang, D. Nykypanchuk, M.M. Maye (2007)

Structural reorganization of 2D NP/DNA system with temperature

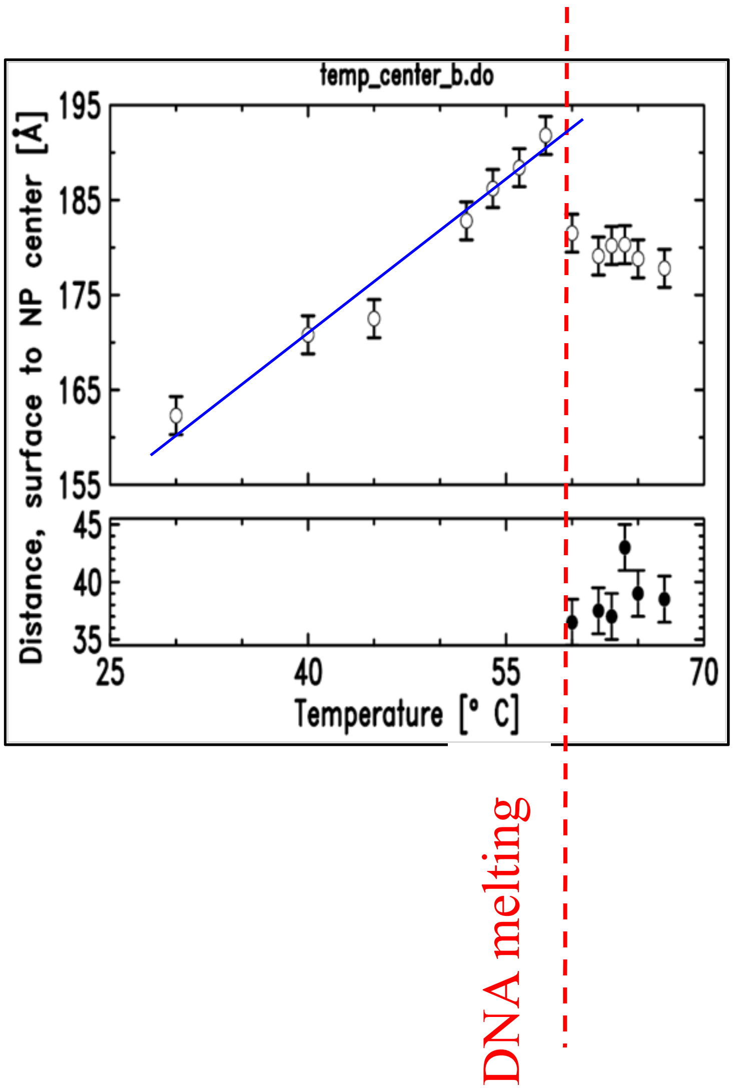


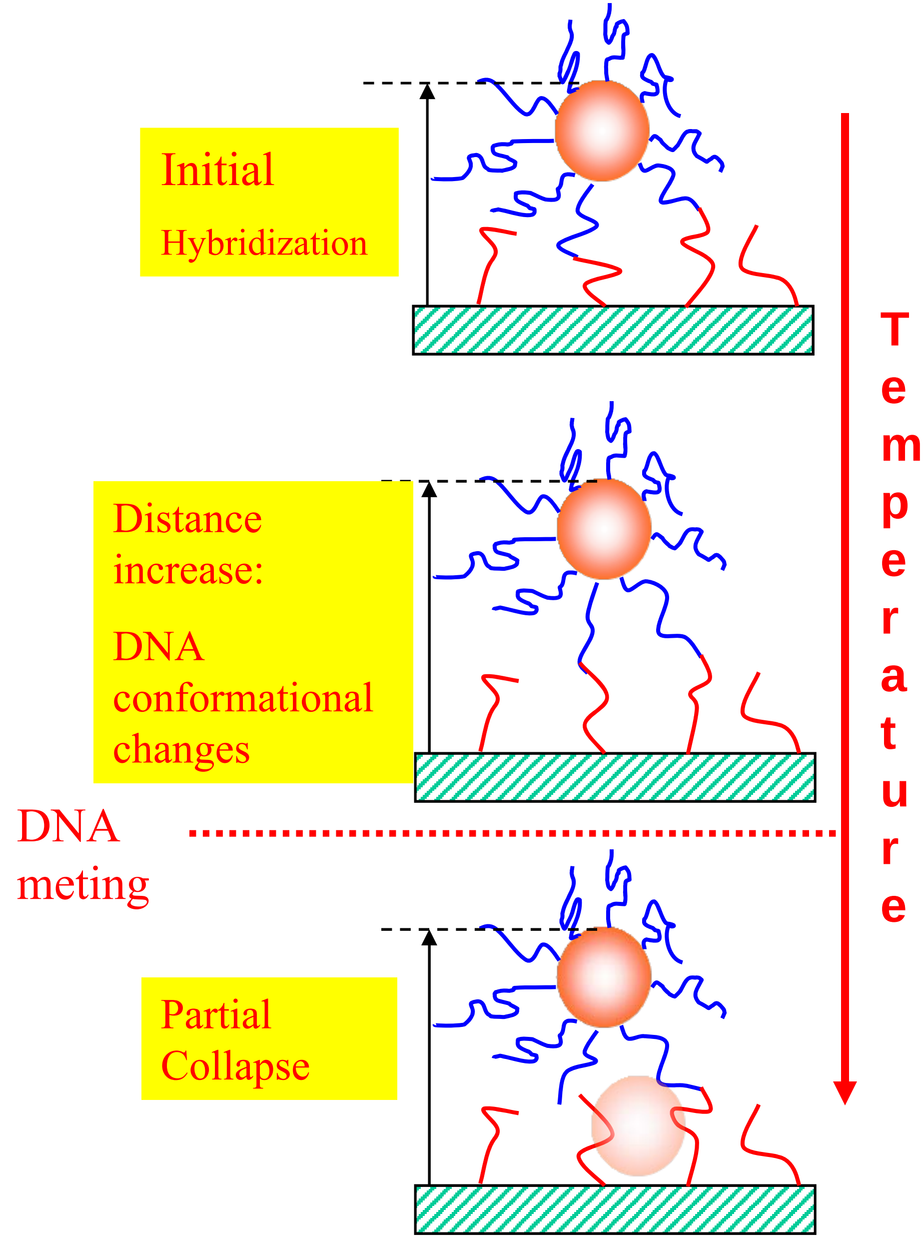


• Particle-surface distance increase with temperature and ($T<T_{melt}$) due to DNA conformational changes.

• Reorganization occurs before and at DNA melting and no further changes in NP-surface distance is observed at $T>T_{melt}$ (60 ^{o}C)

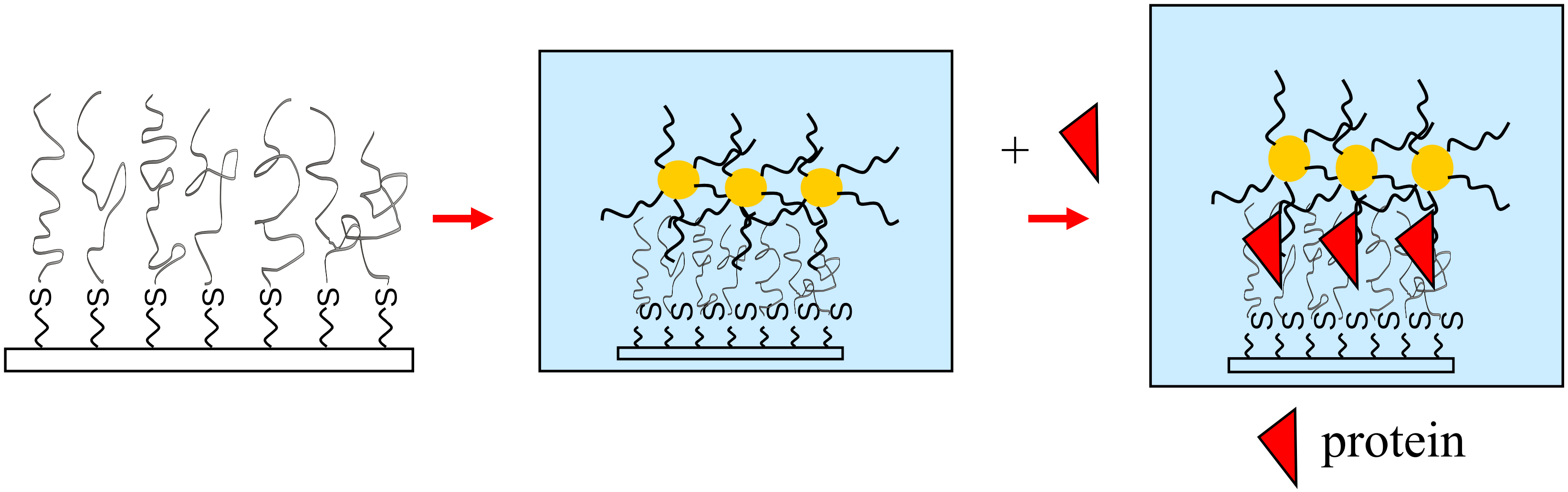
Temperature changes of 2D NP/DNA system





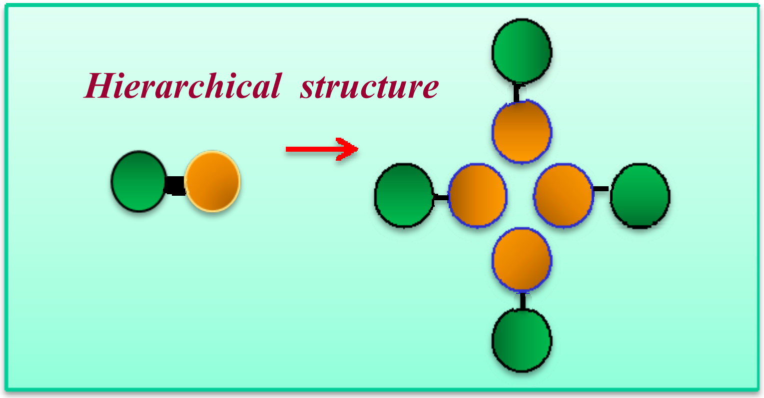
(2007)

DNA Mediated Assembly of Nanoparticles on Surface



- Similar to 3D systems, DNA design principles can be applied to 2D system for regulation of surface-particle/particle interactions
- DNA-protein interactions can be studied using this approach
- Disassembling and dynamic control of 2D system can be achieved using competitive DNA interactions

Nano- “molecules”



Architectured Finite-Size Nanoclusters

Motivations: Emerging physical properties- from “atoms” to “molecules”

Energy/charge transfer in the Engineered clusters

Applications: Bio-sensing, solar energy, etc

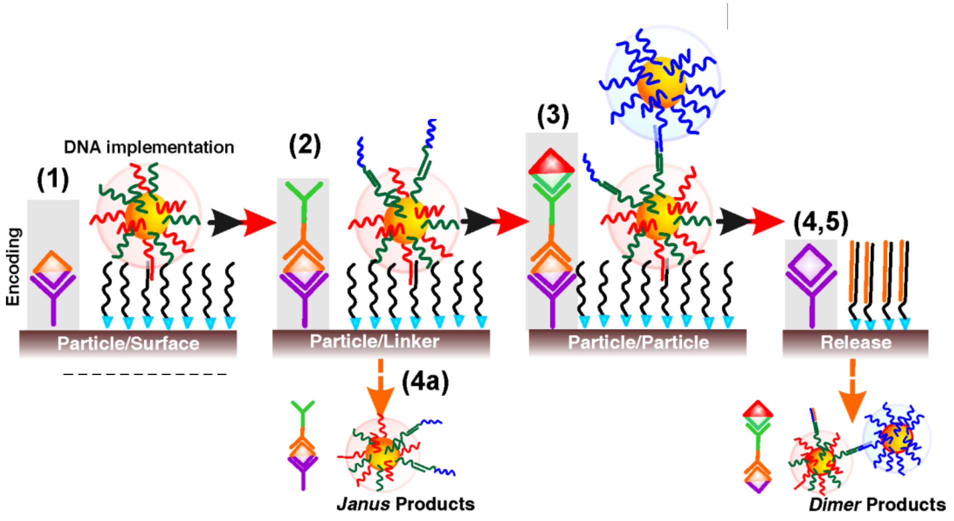
Building Dimer Nano-Clusters

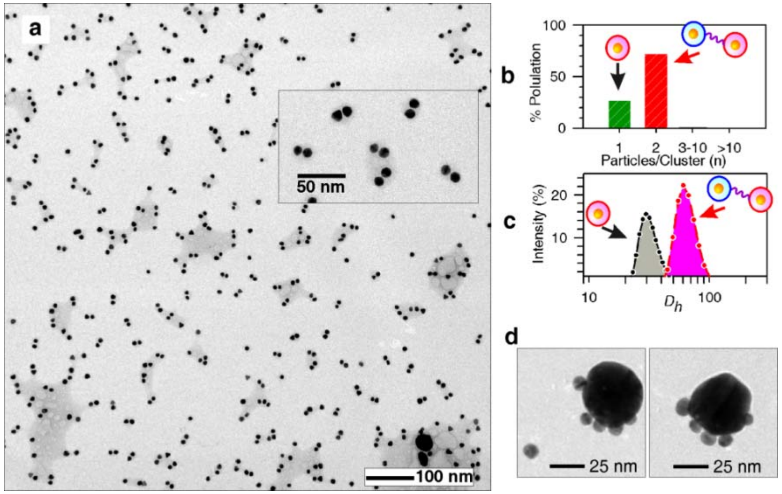
Problem: Solution based nano-assembly methods lead to a broad population of multimers and have low assembly yield.

Cluster Assembly Platform via Stepwise Surface Encoding

Designed clusters with precise placements of nano-components

~75% yield without additional purification



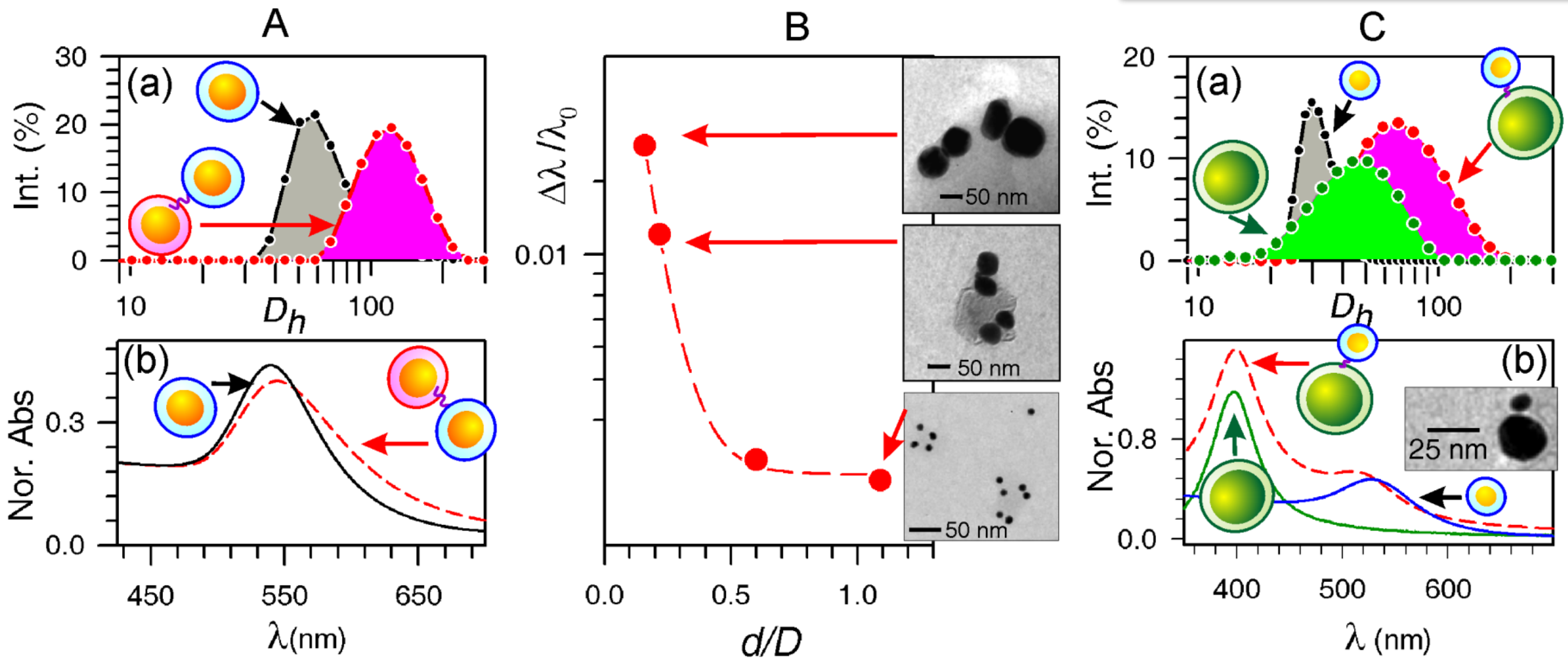


M. Maye, D. Nykypanchuk, D. van der Lelie, O. Gang (submitted), 2008, Patent pending

Optical Properties of Dimer Nanoclusters

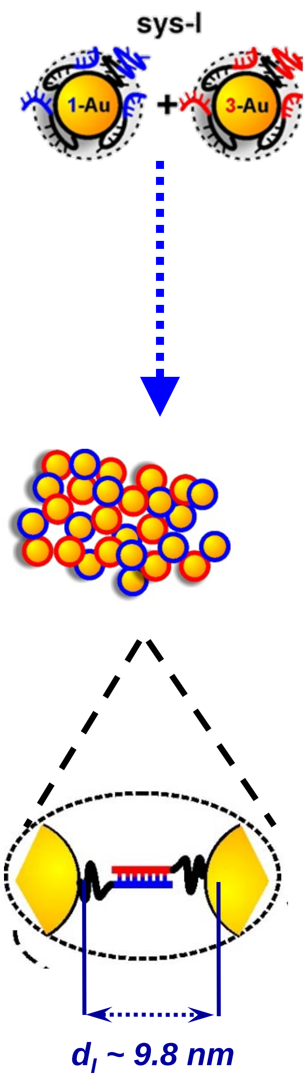
Plasmonic effects in homogeneous dimers

Heterogeneous (Au-Ag) dimer

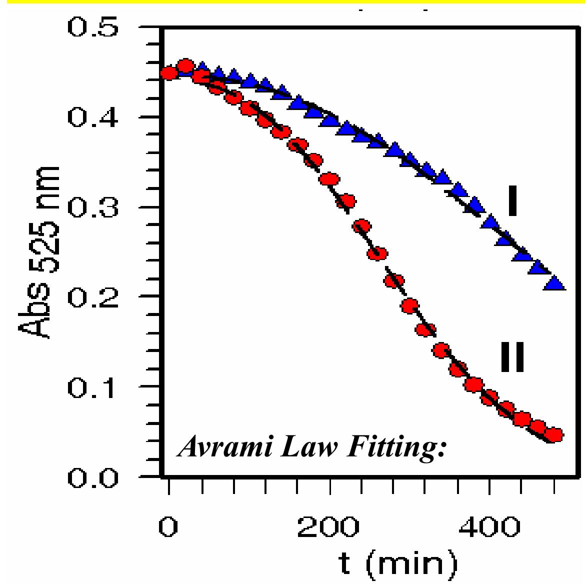


$$\Delta\lambda/\lambda_0 = exp\ (-x/t)+c,\ \ x = d/D,\ t = 0.14$$

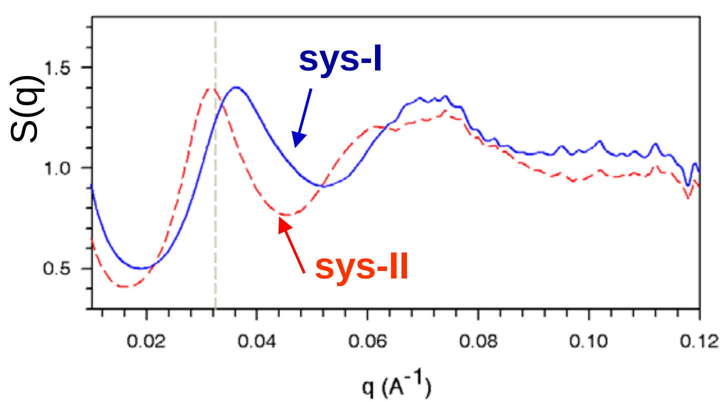
Controlling Kinetics of DNA mediated Assembly

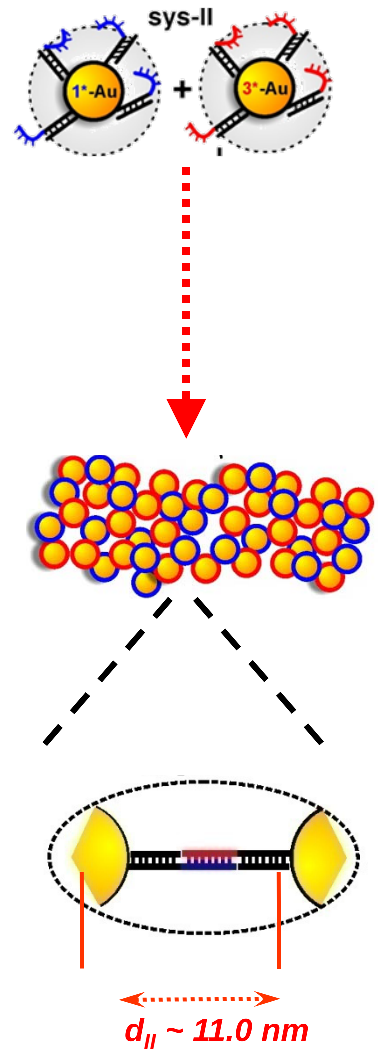


~2x faster kinetics in sys-II vs. Sys-I



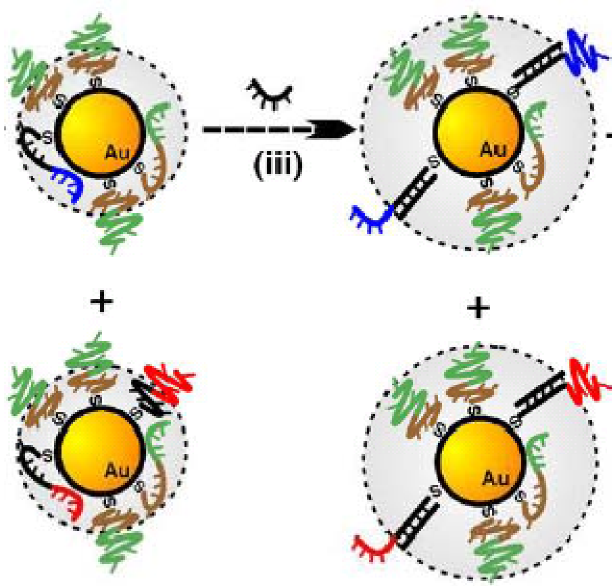
Small Angle X-ray Scattering (SAXS)



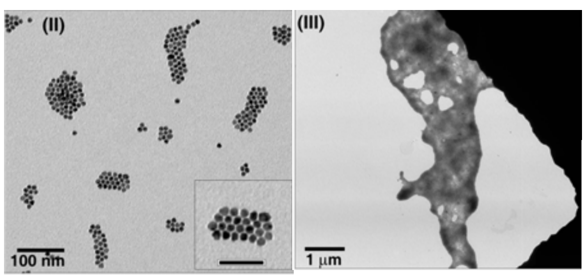


M.M. Maye, D. Nykypanchuk, D. van der Lelie, O. Gang,
J. Am. Chem. Soc. **2006**, *128*, 14020-14021

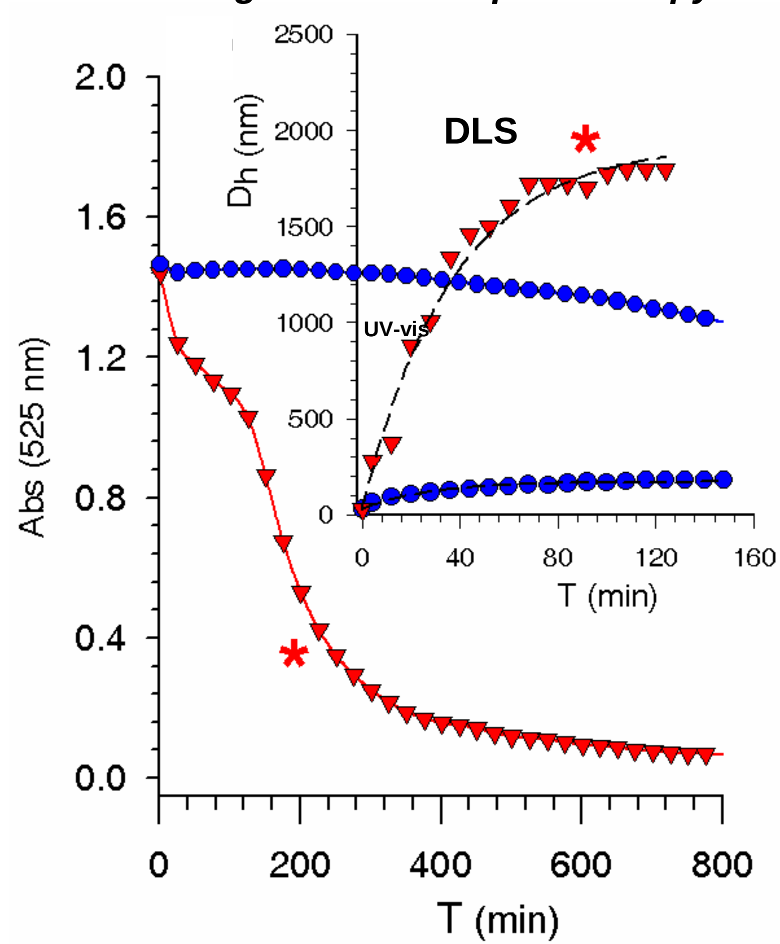
Dynamic control: Switchable Assembly



TEM



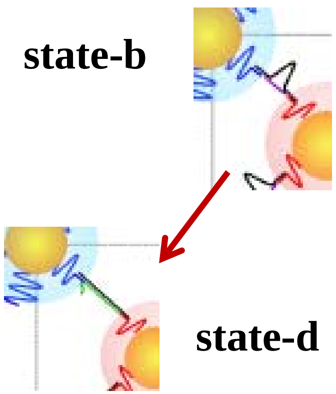
Switching measured by Dynamic Light Scattering and UV-Vis spectroscopy



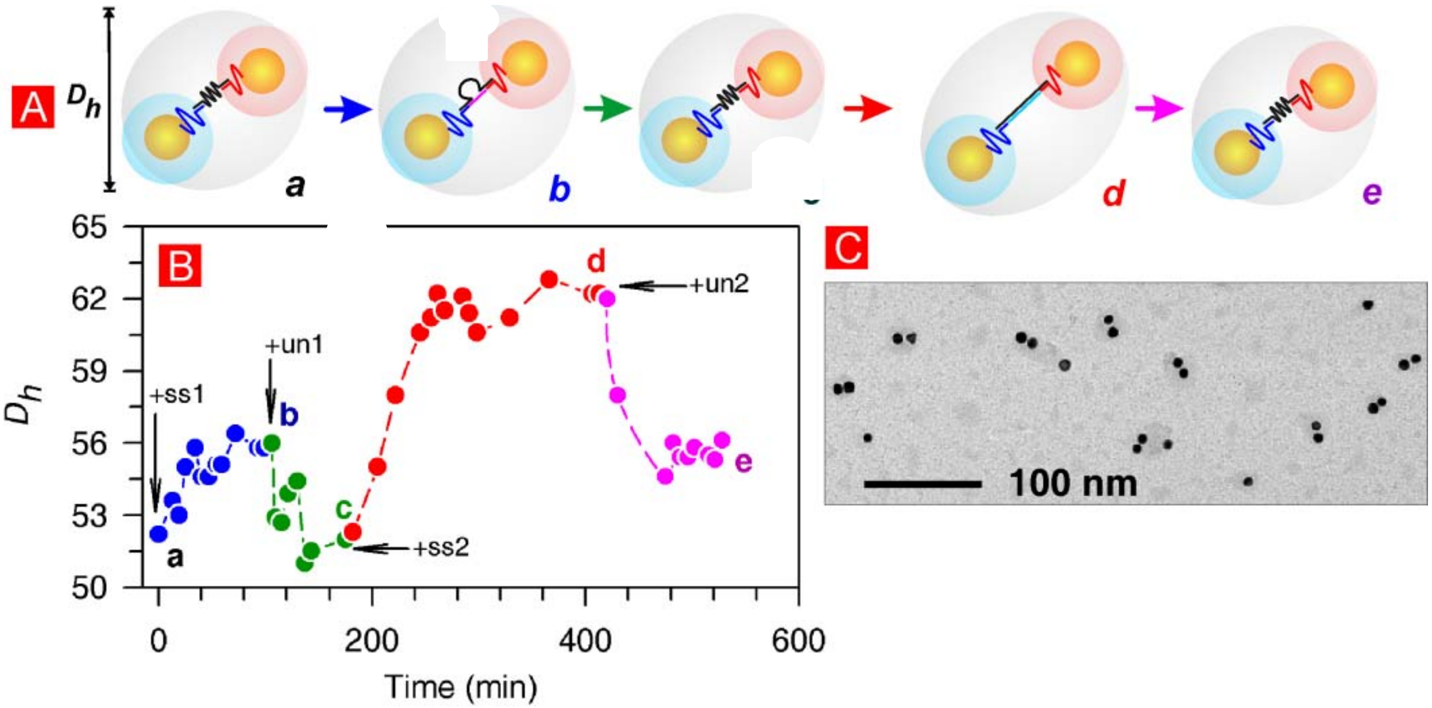
M.M. Maye, D. Nykypanchuk, D. van der Lelie, O. Gang, 2008, in preparation

Reconfigurable Nanosystem

- Design principles for re-configurable system: multiple switchable structural states via incorporation of macromolecular motifs
- Regulated optical respond

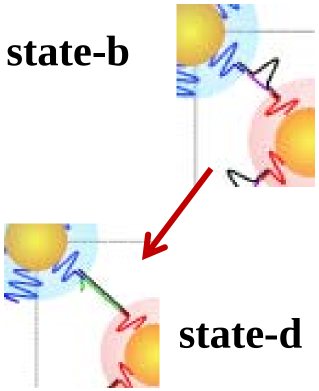


Tunable dimer (0D system)



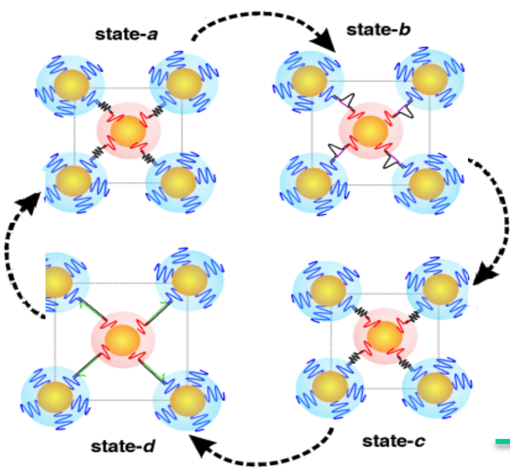
M. Maye, K. Mulige, D. Nykypanchuk, W. Sherman, O. Gang; (2008)

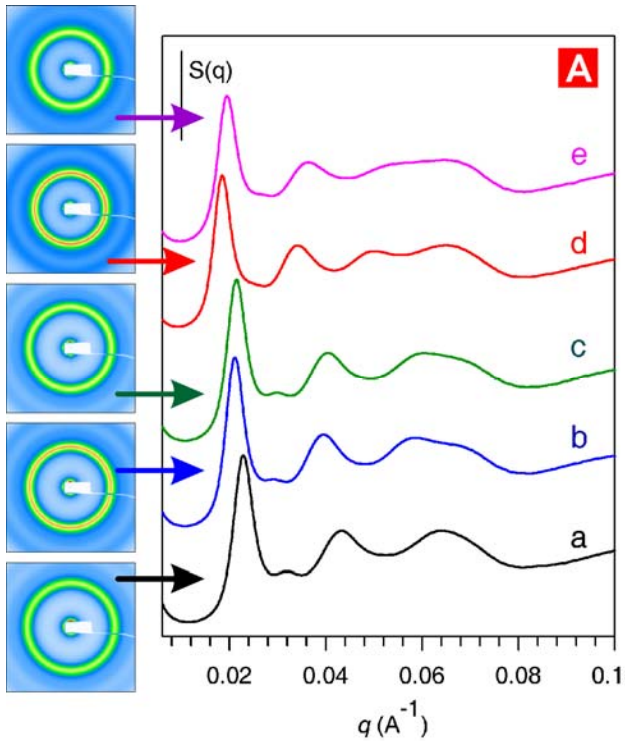
Reconfigurable 3D Nanosystem

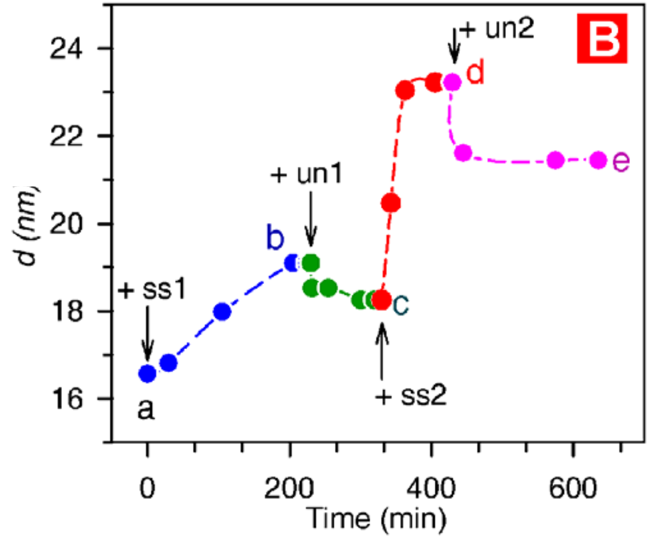


Tunable crystal

3D system



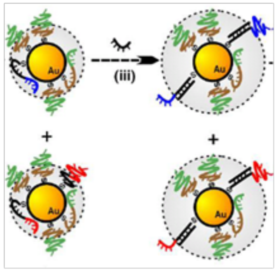




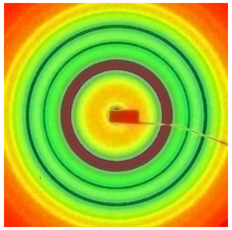
M. Maye, K. Mulige, D. Nykypanchuk, W. Sherman, O. Gang; (2008)

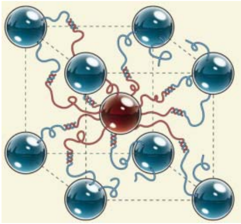
Summary

• **Tuning interparticle potential with preserving particle addressability**

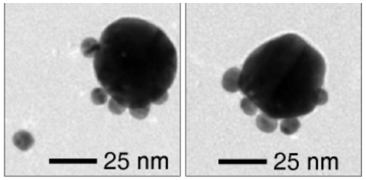


• **Assembly kinetics and switching by tailoring DNA structure, either on the molecular level or via collective behavior**

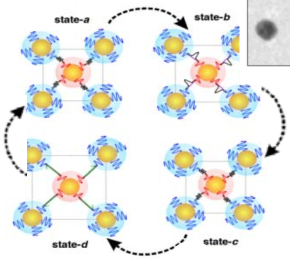




• **DNA guided 3D crystalline phases with intriguing elastic properties**



• **Assembly of dimers, perspectives for rational designed nano-"molecules"**



• **Reconfigurable nano-systems**

"Productivity of DNA synthesis technologies has increased approximately 7,000-fold over the past 15 years, doubling every 14 months. Costs of gene synthesis per bases pair have fallen 50-fold, halving every 32 months.

" Cambridge, MA February 21, 2007 -- Bio Economic Research Associates

Acknowledgments

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Kumara Mudalige
Marine Cuisinier
Bill Sherman
Daniel van der Lelie

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